EIC Detector R&D Progress Report

The EIC Tracking and PID Consortium
(eRD6 Consortium)

December 29, 2017

The Consortium

Project ID: eRD6

Project Name: Tracking & PID detector R&D towards an EIC detector

Period Reported: from July 2017 to December 2017

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1.1 Brief overview of project histories

1.1.1 Brookhaven National Lab

The group at BNL is mainly engaged in optimizing GEM-based micro-pattern gaseous detectors used for reading out a time projection chamber (TPC) installed at the EIC.

We focus on designing the segmentation scheme of the TPC sense plane to optimize the single point resolution for tracks entering the TPC volume. In particular, we have developed highly interleaved zigzag shaped pad designs which greatly enhance charge sharing among neighboring pads and as a result, are able to deliver excellent position resolution with minimal channel count, while exhibiting a virtually uniform response across the detector. We have studied the effects of varying the parameters that define the zigzag geometry using simulations and have measured several PCB's comprising promising zigzag designs in the lab and in beam tests.

Up to this point, we have made good progress with improving the design and performance of the zigzag readouts and have gained a basic conceptual understanding of their behavior. Our primary focus is now to find fabrication processes that precisely reproduce the zigzag patterns since previous fabrications have failed to meet the design criteria, which we believe can potentially affect performance. Specifically, we are pursuing the use of a laser ablation process to produce new zigzag PCB's which should more accurately reproduce our zigzag designs.

In addition to designing the sense plane, we have and continue to carry out investigations aimed at optimizing the performance of the GEM stack. Specifically, the charge transfer efficiency, absolute gain, energy resolution, and ion back-flow are among the features of the GEM that are studied. We also conduct studies to characterize the performance of certain candidate TPC gases, including measurements of the electron drift velocity, charge spread, and attachment. Finally, a longer term goal is to develop a calibration system that produces trails of ionization using a laser to mimic particle tracks within the TPC volume.

1.1.2 Florida Tech

The Florida Tech group is focusing on the development of large low-mass GEM detectors with low channel count for the forward tracker (FT) of the EIC detector.

We designed and implemented radial zigzag strips on large readout PCBs to achieve low-channel count while maintaining good spatial resolution. We constructed a first one-meter-long prototype with such a readout at Florida Tech using a purely mechanical construction technique without any gluing and tested it in beams at Fermilab in 2013. This study showed a non-linearity in the position measurement of hits[1]. The reason was an over-etching of tips and under-etching of troughs in the zigzag strips, which caused insufficient interleaving of adjacent strips and consequently insufficient charge sharing among strips. We adjusted the zigzag strip design to improve the strip interleaving. Small PCBs and a flex-foil with the improved zigzag strip design were produced by industry and by CERN, respectively. We subsequently tested these with highly collimated X-rays at BNL. A substantial reduction in the non-linearity and an improvement in spatial resolution were observed[2].

Next, we designed a second large Triple-GEM detector that implements the drift electrode and a readout electrode with improved radial zigzag strips on polyimide foils rather than on PCBs to reduce the material in the active detector area[3]. These foils were then produced by CERN. To provide sufficient rigidity to this new detector while maintaining low mass, we produced the main support frames from carbon fiber material. We designed the GEM foils for this second detector in such a way that they can also be used for the second UVa FT prototype and for the eRD3 FT prototype being designed by Temple University ("common GEM foil design"). A number of these GEM foil were produced for Florida Tech and UVa by the CERN workshop

using the single-mask foil etching technique. We are currently in the process of assembling this second prototype. Another beam test at Fermilab is planned for summer 2018 to measure its performance.

1.1.3 INFN Trieste

The task of the INFN participants to the eRD6 Consortium is "Further development of hybrid MPGDs for single photon detection synergistic to TPC read-out sensors".

Particle identification of electrons and hadrons over a wide momentum range is a key ingredient for the physics programme at EIC. One of the most challenging aspects is hadron identification at high momenta, namely above 6-8 GeV/c, where the only possibility is the use of Cherenkov imaging techniques with gaseous radiator. The overall constrains of the experimental set-ups at a collider impose a limited RICH detector length and to operate in magnetic fringing field. The use, for this RICH, of gaseous photon detectors is one of the most likely choice. The goal of our project is an R&D to further develop MPGD-based single photon detectors in order to establish one of the key components of the RICH for high momentum hadrons. This R&D has also some aspects synergistic to the development of TPC sensors: the miniaturization of the read-out elements and the reduction of the Ions Back-Flow (IBF).

The starting point are the hybrid MPGD detectors of single photons developed for the upgrade of the gaseous RICH counter [4, 5, 6, 7] of the COMPASS experiment [8, 9] at CERN SPS. These detectors are the result of several years of dedicated R&D [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. They consists in three multiplication stages: two THick GEMs (THGEM) layers, the first one coated with a CsI film and acting as photocathode, followed by a resistive MicroMegas (MM) multiplication stage. The COMPASS photon detectors can operate at gains of at least $3{\times}10^4$ and exhibit an IBF rate lower than 5% [26, 28, 29, 30]. An original element of the hybrid MPGD photon detector is the approach to a resistive MM by discrete elements: the anode pads facing the micromesh are individually equipped with large-value resistors and the HV is provided, via these resistors, to the anode electrodes, while the micromesh is grounded. A second set of electrodes (pads parallel to the first ones) are embedded in the anode PCB: the signal is transferred by capacitive coupling to these electrodes, which are connected to the front-end read-out electronics.

The whole R&D project develops over several years and it includes further improvements of the hybrid MPGD-based photon detectors in order to match the requirements of high momenta hadron identification at EIC and initial tests relative to the application in gaseous detectors of a novel photocathode concept, based on NanoDiamond (ND) particles [31].

1.1.4 Stony Brook University

SBU is putting effort into the study of Ion Backflow (IBF) for a TPC, which is an anticipated device for a central tracker in at least one of the detectors for an EIC. Not only is a TPC considered as the central tracking device but the TPC for sPHENIX has the same physical size when used in, e.g., the BeAST EIC detector.

Based on the TPC that is being constructed for the sPHENIX experiment we performed a comparison between RHIC conditions and EIC conditions. We have shown that we need to re-optimize the TPC when we want re-use the TPC for an EIC detector. In the sPHENIX approach none of the options for minimizing space charge is viable for the EIC. It turns out that the process of re-optimizing a TPC for the principle task of dE/dx measurement results in 0.36× the challenge for the baseline EIC and 3.66× for the ultimate EIC respectively when comparing to RHIC conditions. Weighing these factors against the realization that synchrotron radiation backgrounds are not yet included in the EIC estimates proves that the ultimate EIC TPC device must do more than sPHENIX to achieve the same level of position distortion. Our approach is to investigate new structures in and around the multiplication stage that promise significant better performance when considering IBF.

As indicated by first results new structures can do much better than the results shown by the upgrade

efforts of the ALICE TPC. As part of our EIC-specific TPC R&D we wish to perform bench tests of this phenomenon at Stony Brook to pursue a better figure of merit than sPHENIX to enable the use of the TPC at the ultimate EIC luminosity. We will use both equipment borrowed from our colleagues at Yale University as well as newly purchased devices for these measurements.

Another project at SBU is to provide a unit that allows to produce high quality large size mirrors for RICH applications. This project is ongoing and was held back several times due to unforeseen circumstances in the environment of the evaporator device in our clean room.

1.1.5 University of Virginia

The focus of the group at UVa is the development of high performance, large and low mass GEM detector for the forward region of an EIC detector.

Our R&D at UVa shares some similarities with the development by the Florida Tech group and by Temple U. group within the eRD3 program but we are specifically focused on the development of high performance, large area two dimensional U-V strip readout with fine pitch to provide excellent spatial resolution in both radial and azimuthal direction. A first prototype of such detector was built and successfully tested in test beam at the Fermilab Test Beam Facility (FTBF) in 2013. The analysis of the test beam data fully validated the expected performances of the U-V strip readout and the results were published in [32].

We are going through the second phase of the R&D with a design improvement of the U-V strip readout to push even further the spatial resolution capabilities in both dimensions. The new prototype is conceived around the "Common EIC GEM foil design" jointly developed by UVa, Florida Tech groups of the eRD6 consortium and in collaboration with Temple University eRD3 group. We have also been testing new ideas such as the ultra low mass Chromium GEM foil to reduce even further the material budget of EIC-FT GEM detectors and the development of the double-sided zebra connection scheme to provide an elegant solution for the fine pitch U-V strip readout layer. These innovative ideas will ultimately be integrated in the final design of the large area EIC forward GEM trackers.

We currently are in the process of starting the assembly of the second prototype that we hope to complete in a few months and test in the second test beam campaign at the FTBF in summer 2018.

1.1.6 Yale University

Nothing to report.

1.2 What was planned for this period?

1.2.1 Brookhaven National Lab

1. ***Zigzag pad development***: We planned to continue the development and optimization of the zigzag pads, with a focus on pursuing more accurate fabrication methods. In particular we planned on fabricating new PCB's with zigzag patterns using a novel laser ablation (or "laser etching") process that very precisely removes copper from a PCB substrate to shape the electrodes of the readout plane. This technique promises to reproduce the fine features of our new zigzag designs down to the level of 10-20 microns. As a result, this process enables the gap between adjacent pads to be reduced from the standard 3mils (~75μm) to 1mil (~25μm), which significantly extends the range over which this and other parameters of the pad geometry may be studied.

2. ***GEM based cosmic ray telescope***: We planned to build a 4-layer cosmic ray telescope for the purpose of providing high precision reference tracks for a detector under test. We plan to use these

particle tracks for measuring the position resolution of a GEM detector equipped with one of our zigzag PCB's.

3. ***GEM Studies using TPC gas mixtures***: We planned to continue to study various candidate gas mixtures optimal for a TPC. In particular, we hoped to have some results from the following set of measurements related to 1) the TPC drift volume: charge spread due to transverse diffusion, the number of primary ionization electrons created in the gas due to the passage of an energetic particle, drift velocity, and attachment, and 2) the GEM stack: charge transfer and extraction efficiency, absolute gain, energy resolution, and ion back-flow.

1.2.2 Florida Tech

Our main goal for the past six months was to complete procurement of missing components for the new one-meter-long FT GEM detector with zigzag readout, assemble it, and put it through a battery of quality control (QC) tests modeled on the QC for the large GEM detectors of the CMS forward muon upgrade.

In parallel, we planned to finalize a publication on the results of the X-ray studies of small improved zigzag readout boards that were reported in the Jan 2017 eRD6 report.

1.2.3 INFN Trieste

Activity planned in period July 2017 - December 2017

Three R&D items were foreseen in this period, two of them related to the activity planned for the FY 2018, namely:

1. the completion of the test of **novel materials for the THGEM PCB** *(2017 activity)*;
2. the continuation of the development of **resistive MM by discrete elements with miniaturized pad-size** *(2017 and 2018 activity)*;
3. the initial studies to understand the compatibility of an **innovative photocathode based on NanoDiamond (ND) particles** with the operation in gaseous detectors and, in particular, in MPGD-based photon detectors *(2018 activity)*.

1.2.4 Stony Brook University

It was planned to install the evaporation equipment that has been obtained in the appropriate evaporator unit. It was planned to start-up and the performing of the evaporation process with a specialist at Stony Brook University.

As another project, we are in the process of obtaining funds for the proposed work to perform studies for a Time Projection Chamber to be used in an EIC detector.

1.2.5 University of Virginia

For the current six months, our plan was toe:

- Complete the assembly of the prototype after all the parts are produced and perform preliminary tests with cosmics and x-ray source
- To prepare for the Beam Test at Fermilab in summer 2018.

- Continue the aging test for the Cr-GEM chamber with x-ray in moderate flux to monitor the long term performances of the chamber.

1.2.6 Yale University

Nothing to report.

1.3 What was achieved?

1.3.1 Brookhaven National Lab

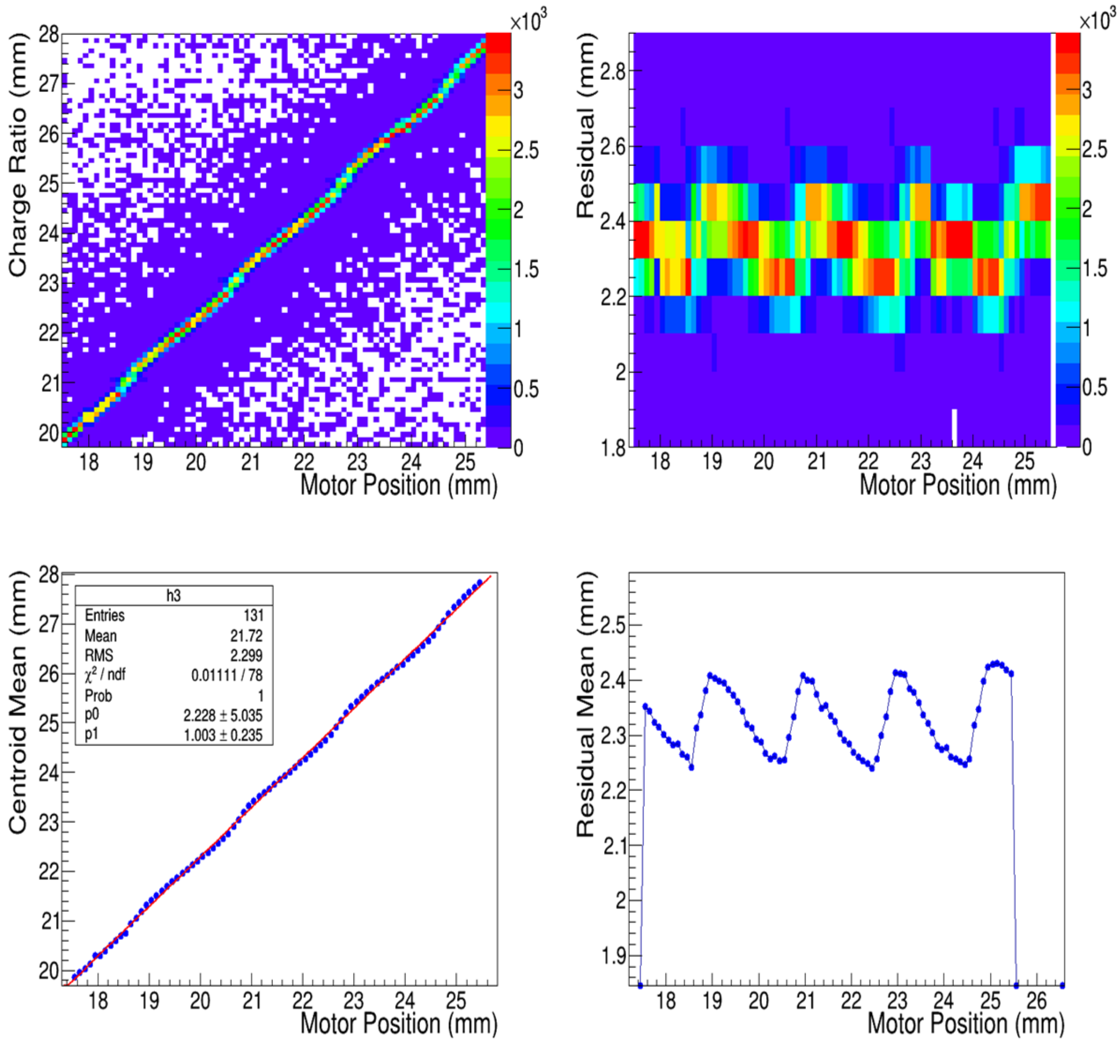

Figure 1: The top left scatter plot shows the reconstructed hit position vs. the motor position (ie, the actual hit position of each x-ray modulo the width of the beam) and the right scatter plot shows the corresponding residual vs motor position. The bottom plots show the respective averages of these quantities, which more clearly depict the prevalent differential non-linearity.

1. ***Finalized measurements of first zigzag PCB***: Last time we reported on the linearity of response

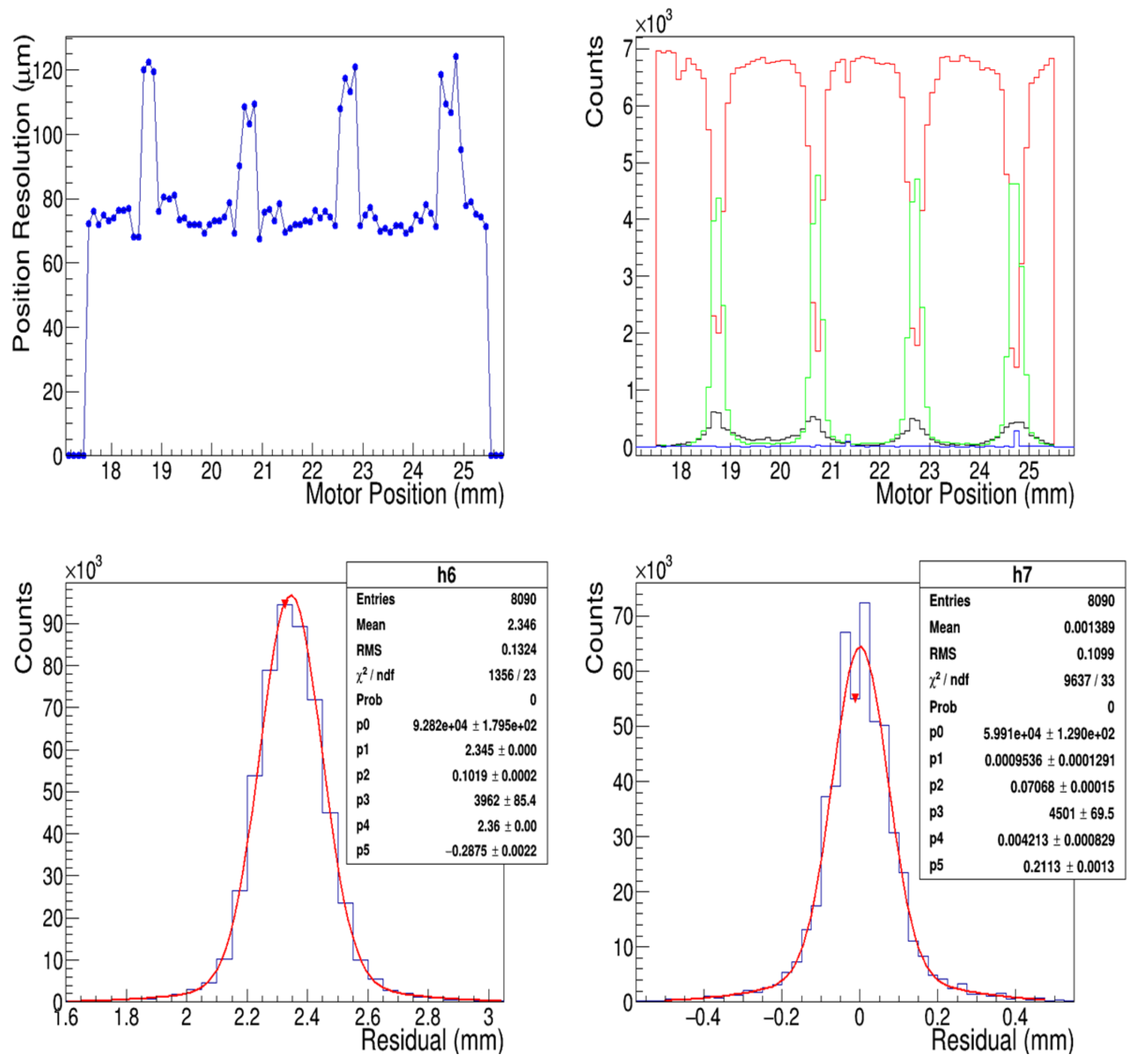

Figure 2: Top: position resolution and number of pads above threshold vs. actual hit position, respectively. For the plot on the right the black histogram corresponds to the number of single pad hits, red: 2-pad hits, green: 3-pad hits, and blue: 4-pad hits. The integrated percentage of single pad hits is only 2.6%, leaving 97.4% of the events with useful hits Bottom: position resolution integrated over several pitch cycles, with and without the DNL folded into the residual distribution, respectively. The centroid is calculated using only two-pad and three-pad hits.

of the reconstructed hit position vs. the actual hit position of x-rays entering a 4-GEM equipped with a newly designed zigzag PCB. The results showed a peculiar piece-wise correlation. However, since then it has been determined that this behavior was essentially due to the fact that the particular set of electronics (ie, SRS sytem with APV25 front end electronics) we used necessitated operating our detector at very low gain, which greatly biased the results. In particular, the peripheral pads of many clusters fell below the noise threshold, resulting in single pad hits (ie, $> 30\%$ of events) which were eliminated from the analysis. In addition, many three pad clusters were observed as two pad clusters. The combination of these biases created a very particular mixture of two and three pad clusters as determined by the analysis that gave rise to the observed piece-wise correlation.

Since then we have used alternate electronics which allowed for the possibility to operate at more standard values of gain. The corresponding results are shown below in Fig. 1 and 2. As can be seen, here the correlation plots are continuous, with an average slope of ˜1, as expected. Furthermore, the

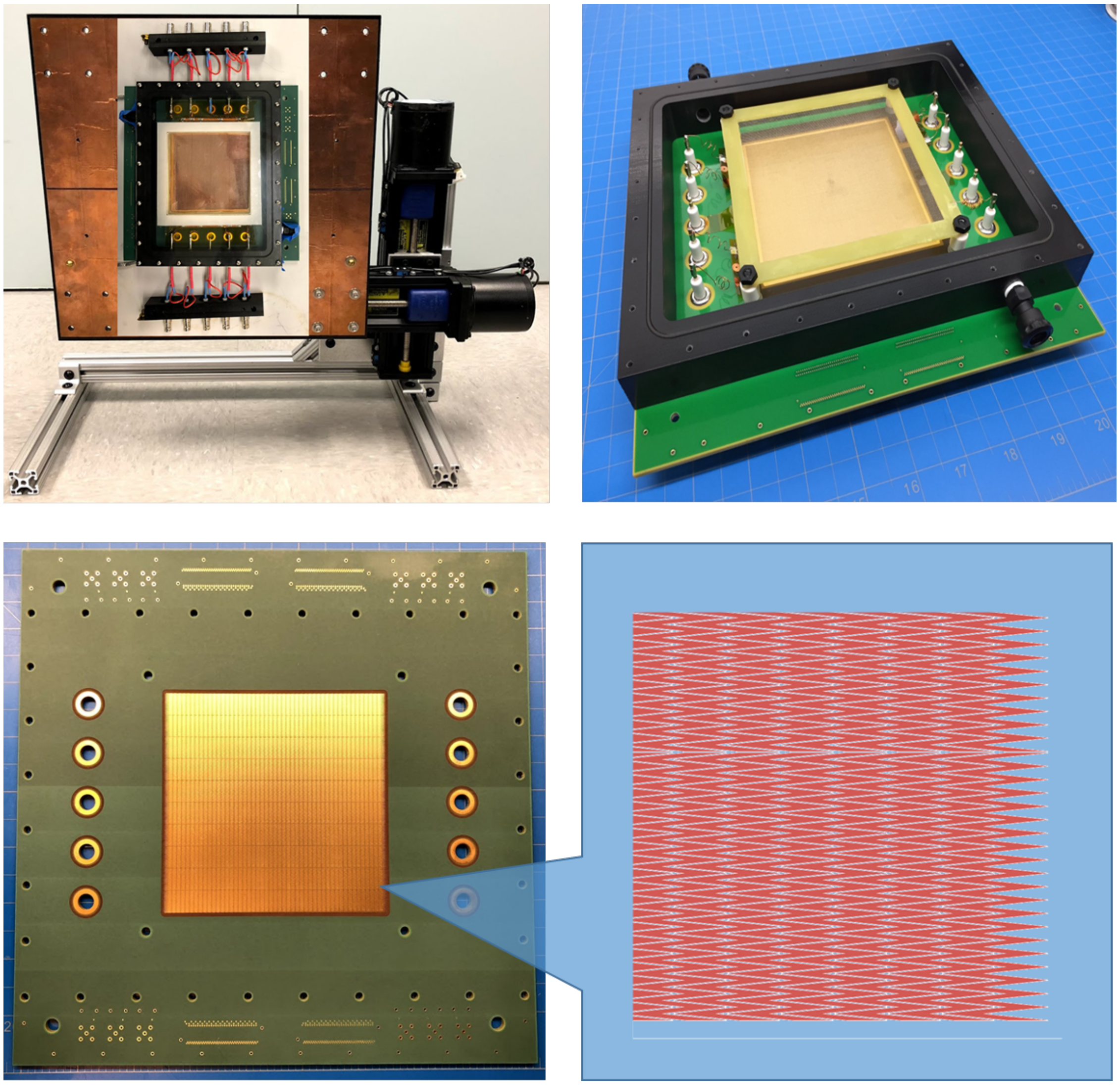

Figure 3: Top: XY-movable detector stand (left) for a 4GEM, equipped with zigzag PCB (right). Bottom: Zigzag PCB with zoomed-in inset depicting the zigzag pattern (right) (Note: the PCB shown here is not the one to be used in the beam test since it has not been produced yet.)

position resolution, integrated across several pitch cycles is about 100μm when the full differential non-linearity is included, however, it is about 70μm (albeit with longer tails in the distribution) when it is corrected for. These numbers are quite impressive considering the almost order magnitude improvement from the resolution implied by the pad pitch alone. Also, the number of single pad hits is reduced to <3%, over the older zigzag designs for which almost 30% of the events contained single pad hits.

The method by which the centroid was calculated used a charge threshold to identify hits to form 2, 3, and 4-pad clusters from which the centroid was derived. However a more straight forward approach was also implemented that does not utilize a threshold cut. Rather the peak with maximum charge is identified and a contiguous three pad cluster is always formed around it by maximizing the total charge. While such a method allows for the additional influence of noise, the centroid response tends to be more flat. In this case, since the N/S was quite low, the results from the two methods were quite similar, with the benefit that the "three-pad method" requires less computation. Furthermore, the three pad method also insures virtually 100% efficiency, but this may come at the cost of worse resolution in instances where charge sharing is not optimized.

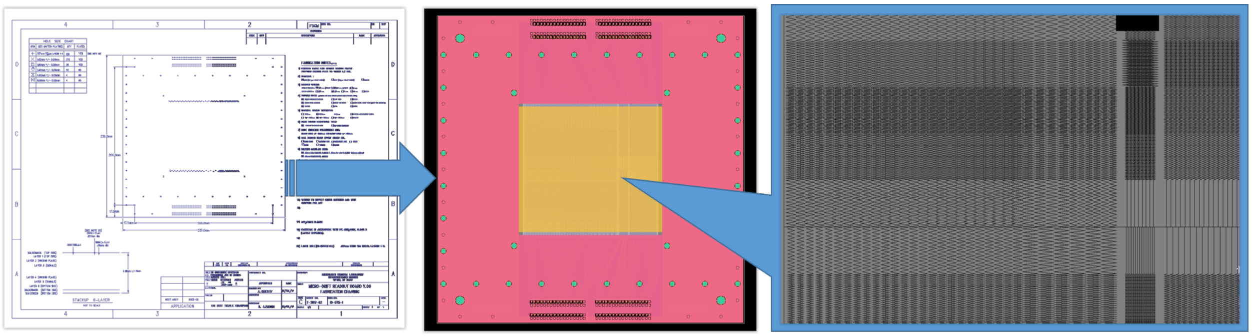

Figure 4: Fabrication drawing for the multi-zigzag PCB, in addition to the PCB layout and a zoom-in on a multitude of zigzag geometries.

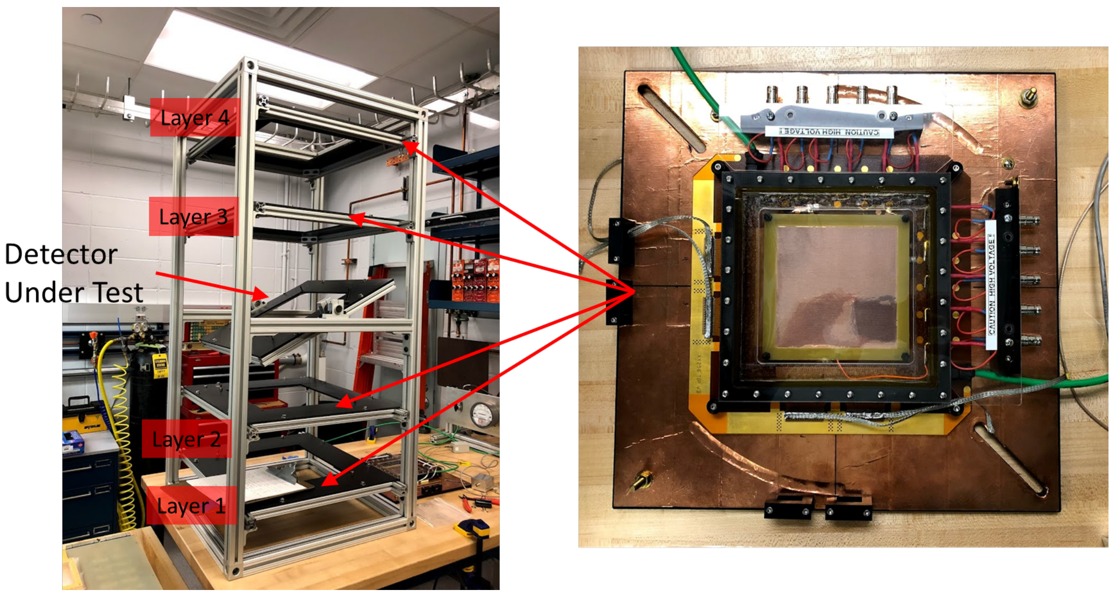

Figure 5: 4-layer GEM-based comic ray telescope. Shown is the telescope stand where each GEM layer is mounted and an assembled 3-GEM layer with COMPASS readout on the right. In the center of the stand the detector under test is mounted to a rotatable platform.

While the performance of the zigzags has improved considerably since the last design iteration, we feel that this design is still far from ideal due to the prevalence of the relatively large differential non-linearity still present in the data. We feel that while the implications of the design parameters are starting to be well understood, the effects of manufacturing distortions still largely influence the readout performance and are difficult to compensate for. Therefore we are pursuing new fabrication methods that are free from the distortions in the zigzag geometry described last time, including over-etched tips, and under-etched troughs. For example, newer methods that utilize laser ablation can very precisely reproduce the finer features of our new zigzag designs and also offer more flexibility in the gap spacing between adjacent pads. Though it is not fully clear at the moment how much the gap widths affect the linear response of the pads, the laser ablation process will allow this parameter to be studied down to a 1mil gap spacing, well below the gap width of 3mils produced in more standard etching processes.

2. ***Preparation for beam test of multi-zigzag PCB at Fermilab Test Beam Facility***: We are planning a beam test of a newly designed multi-zigzag PCB at the Fermilab test beam facility (FTBF) in March. The PCB will be coupled to a quadruple GEM detector and will consists of 128 regions,

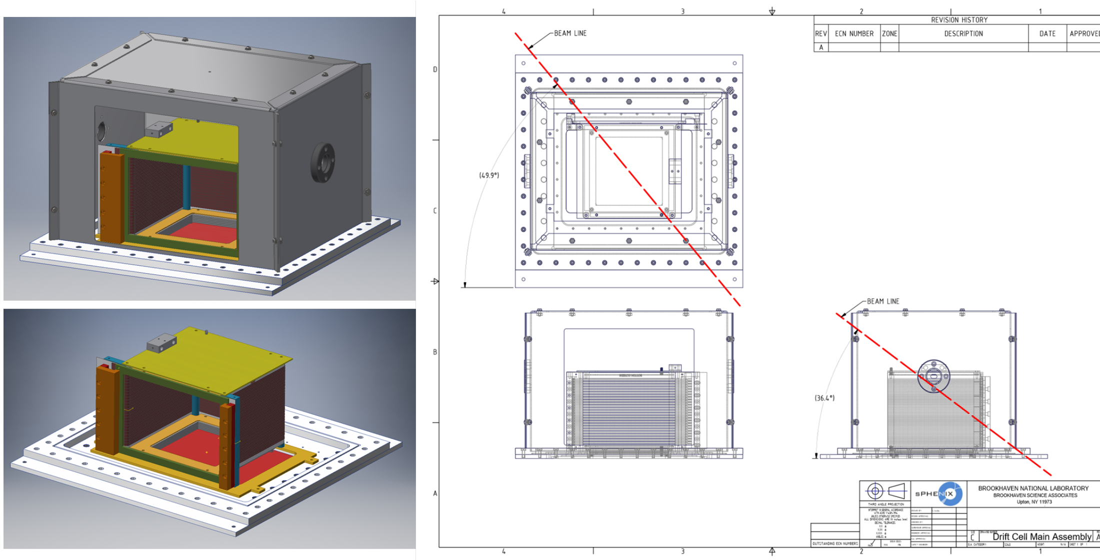

Figure 6: Left: 3D model of compact TPC prototype. The detector consists of a 10cm x 10cm x 10cm field cage, and a 4-GEM readout with a zigzag sense plane, housed in an aluminium sheet metal enclosure which provides the gas seal. Right: Engineering drawing of the TPC prototype showing the maximum angle of incidence for tracks entering the detector volume defined by the size of the entrance and exit windows (made of mylar).

each with a unique zigzag shaped pad geometry. Each region will consist of 4-5 pads and will make up an area of about 10x10 mm^2. As mentioned, the PCB will be fabricated using a laser ablation process which can produce gap widths as small as 1mil. Thus, the gap width between adjacent pads in our newest PCB will be fixed for the entire board at the smallest possible value and the pad pitch will range from 0.4 – 3.33mm, with a the zigzag periodicity ranging from 330-1000μm. The detector will be mounted to a XY-movable stand such that the beam axis is normally incident with respect to the readout plane, at least initially. Fig. 3 illustrates how the detector will be mounted to the detector stand as well as its internal make-up. As the XY-table translates the detector in a plane orthogonal to the beam axis, this allows the beam to scan across each zigzag geometry.

At this point, the design of the multi-zigzag pattern PCB has just been completed (see Fig. 4) and a printed circuit card manufacturer that utilizes the laser etching process has been identified (TTM Technologies). By communicating with experts at this company we have learned a great deal about the laser etching process in order to optimize the PCB design within the fabrication limitations.. Though the full PCB consists of four layers, only the top layer will be laser etched to save on cost. Finally, the movable XY-stand has been built but requires further revision based on feedback from experts at the Fermilab test beam facility.

3. ***Four layer, GEM-based cosmic ray telescope***: As mentioned in earlier reports, we have designed a 4 layer GEM-based telescope, for use in the lab to precisely measure reference tracks for determining the position and angular resolution of any detector under test. The telescope will be primarily used to study the position resolution (and possibly the angular resolution) of a 4-GEM detector equipped with a specific zigzag pattern. The resolution determined from real tracks will nicely compliment the resolution studies of a detector under test using the x-ray scanner (described below). The assembly of the apparatus is nearing completion where the construction of the overall frame structure is now complete. This structure holds each detector layer in space at a specific inclination with respect to the detector under test, as shown in Fig. 5. The assembly of each detector layer has already begun and we anticipate the completion of the telescope as a whole over the next month or so. Each tracking layer is comprised of a 3-GEM detector coupled to a COMPASS readout plane and will be read out using the SRS/APV25 front end electronics, for which we have procured 2048 channels. (It should be noted that

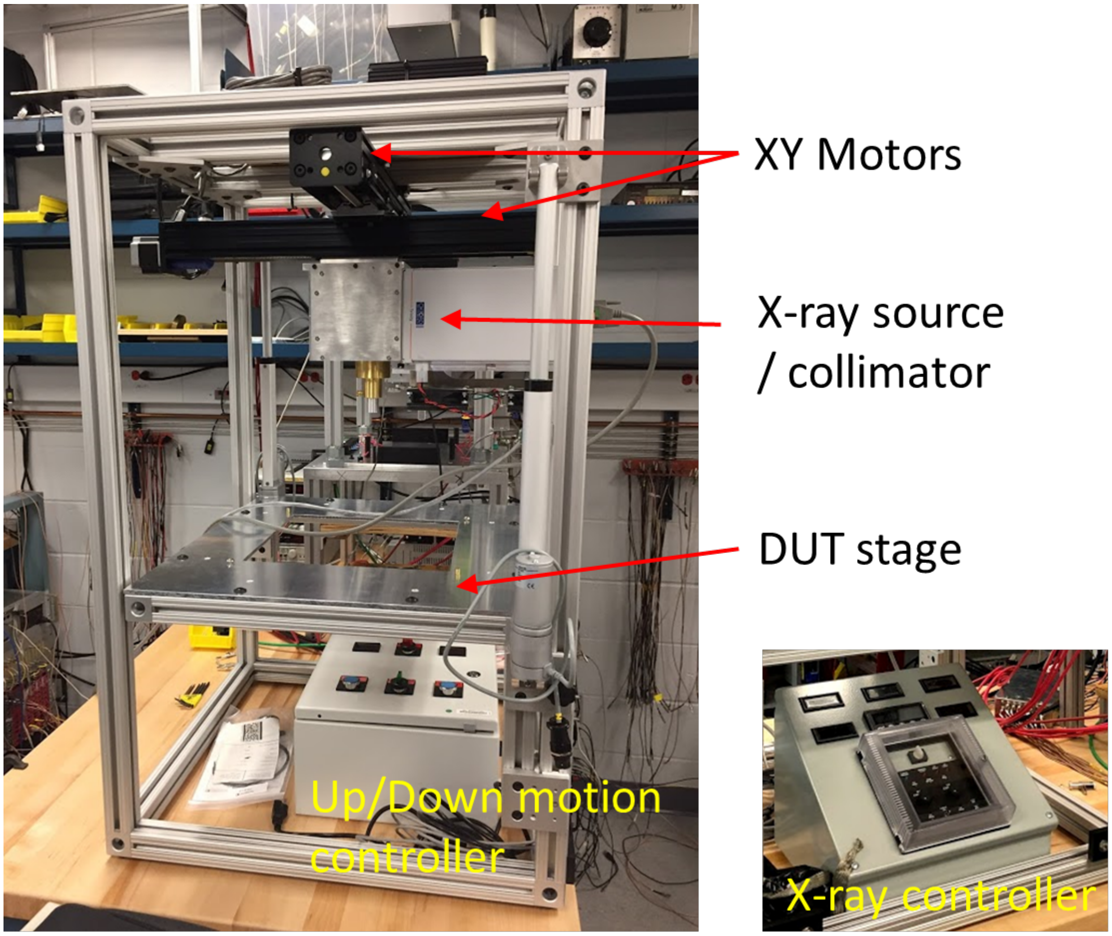

Figure 7: High intensity x-ray scanner with high precision XY motors which translates the x-ray source across the acceptance of the detector under test (DUT) with a travel of up to 15".

while the SRS/APV25 electronics seem to be adequate for reading out the COMPASS X-Y strips, they are generally not optimized for the larger area zigzag pads that make up our zigzag PCB's. Typically the charge from the GEM is shared among just 2-3 pads for the zigzag PCB, but is split among 5-10 X-Y strips for the COMPASS board.) Once the telescope is fully operational after commissioning in the lab, it may be used as an ancillary reference tracker for our beam test in July 2018, as well.

4. ***Compact TPC prototype***: A small TPC prototype detector has been designed and is currently being built for the purpose of reconstructing ~10cm particle track segments using a 10cm cx 10cm x10cm field cage coupled to newly developed zigzag PCB's. The detector will also be intended for characterizing various candidate TPC gases. We have adapted the design of the combination TPC-Cherenkov prototype detector [33] used last year by removing the Cherenkov portion of the detector and thereby have reduced its overall size. An engineering rendering of the prototype is shown in Fig. 6.

5. ***High intensity x-ray scanner, with large stage***: We have designed a high intensity x-ray scanner with a large stage for the purpose of more rapidly completing the x-ray scans that characterize various PCB's under study, including the many zigzag PCBs we have only partially scanned using our old x-ray scanner setup. The existing 3W x-ray tube setup takes almost 24 hours to complete a scan. However, the new scanner employs a 40W tube with a significantly smaller cone of illumination, which should increase the rate of delivered photons by many factors. The larger stage of the new setup also allows

for up to 15 inches of travel for the x-ray source so detectors much bigger than the typical test-bench detector may be scanned, including the larger modules intended for use in beam-line experiments.

The x-ray scanner has been fully assembled and was tested. However the detected rate of collimated photons turned out to be much less than anticipated due to the presence of certain window materials used in the new x-ray tube. We are therefore developing a scheme to recuperate the lost rate by utilizing a doubly curved diffractive crystal optic which both selects wavelengths of interest for a monochromatic output as well as collects and focuses the beam instead of simply collimating it. We are in contact with various manufacturers of crystal graphite monochromators for this application and are in the process of getting quotes. A picture of the x-ray scanner is shown in Fig. 7.

Publication of results:

1. A manuscript entitled: "Beam Test Results from a GEM-based Combination TPC-Cherenkov Detector" is almost complete and will be submitted to the IEEE journal, Transaction on Nuclear Science within the next few months. Consortium members from Stony Brook Univ. and BNL are co-authors for this paper.
2. A manuscript entitled: "Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors" summarizes the results from our latest R&D efforts with zigzag geometries and was very recently submitted to the IEEE journal, Transaction on Nuclear Science. Consortium members from FIT, Stony Brook Univ., and BNL are co-authors for this paper.

Conference presentations:

1. B. Azmoun presented the results from the TPC-Cherenkov beam test in a talk at the MPGD2017 conference at Temple U. in Philadelphia.
2. B. Azmoun presented the results from our zigzag R&D efforts in a poster presentation at the 2017 IEEE Nuclear Science Symposium in Atlanta.

1.3.2 Florida Tech

Construction of next full-size EIC Forward Tracker GEM detector prototype We abandoned the idea of producing various components for the detector mechanics in collaboration with a local company as the company remained unresponsive to our inquiries. Instead, we produced the pullout posts that are used to stretch the foils ourselves by 3D-printing them on campus. We also 3D-printed the inner frame pieces that sandwich the foils in a stack. Fig.8 shows a test assembly of these posts and inner frame pieces with the carbon fiber frames. The resulting structure is quite rigid mechanically as anticipated from our CAD simulation, which is promising for its ability to take up the tension of the five stretched foils.

An outer frame made from epoxy-fiberglass material was procured from the CERN workshop (Rui De Oliveira). Fig.9 (left) shows the 16 mm tall frame with an O-ring inserted into a groove. This O-ring and a similar one at the bottom of the frame seals the outer frame against the carbon fiber frames. A first test assembly of the outer frame with the carbon fiber frames showed a good fit of the outer frame around the pull-out posts and a visual inspection showed proper sealing via the O-rings. A 1-mil-thick aluminized kapton foil was procured from industry. Sections of this foil are being stretched across the outside of each carbon fiber frame and glued to the frames to provide a gas window and close the gas volume (Fig.9 right). The aluminization will prevent water from diffusing across the thin kapton foil into the detector. A new flex-circuit foil was designed that is needed for connecting the foils inside the gas volume to an HV divider circuit outside the gas volume. The design has been submitted to the CERN workshop for production. We have also produced a mock-up of the five-foil stack made from paper "'foils" that we will use to ensure that pull-out posts, foils, and inner frames align up properly all around the perimeter and to test the stretching of such a stack.

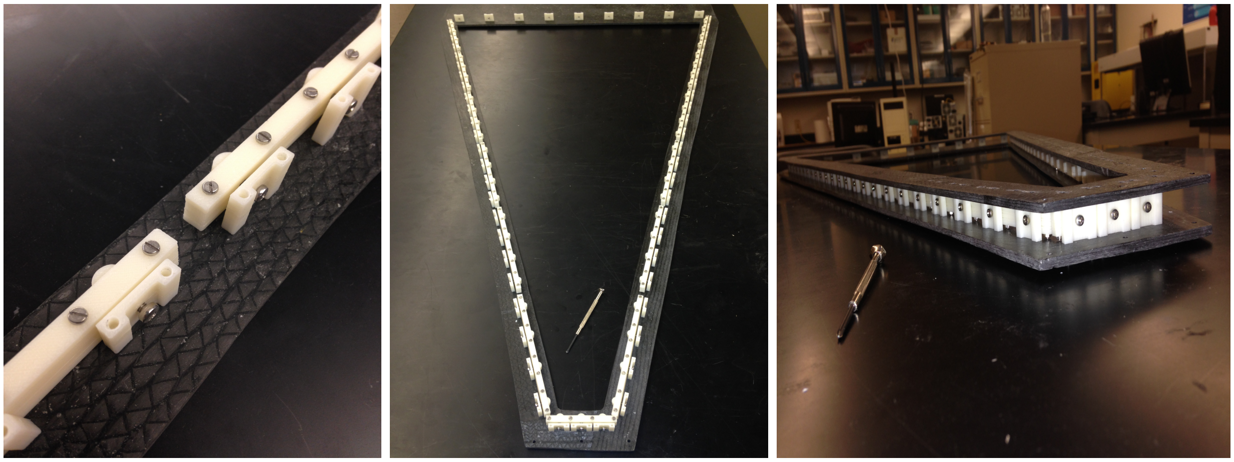

Figure 8: Test assembly of Florida Tech forward tracker prototype with 3D-printed pull-out posts and inner frame pieces mounted on one carbon fiber frame (left and center) and sandwiched between both carbon fiber frames (right).

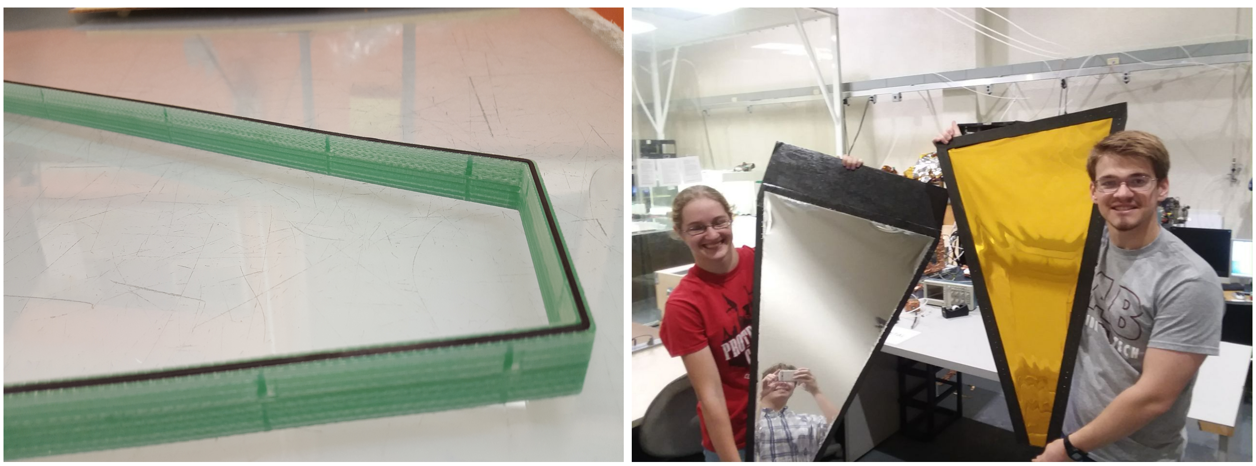

Figure 9: Outer frame with O-ring (left) and Florida Tech EIC undergraduate research students holding carbon-fiber frames covered with aluminized kapton foil (right) for Florida Tech Forward Tracker prototype detector.

Table 1 gives an accounting of the material in the active area of this detector prototype in comparison with a standard large triple-GEM detector made from PCBs. The total material, which is dominated by the copper on the various foils, is about 0.6% of a radiation length .

Publication of results from X-ray studies of 10 cm $\times$ 10 cm zigzag boards A manuscript describing results on the performance of improved zigzag readout structures was submitted to NIM A[2]. Consortium members from Florida Tech and BNL are co-authors of this paper. NIM A reviewer comments were received and addressed in a revised version that was submitted to NIM A on Dec 5, 2017.

Conference presentations M. Hohlmann presented the status of Florida Tech R&D for the EIC Forward Tracker in talks at the MPGD2017 conference at Temple U. in Philadelphia and at the 2017 IEEE Nuclear Science Symposium in Atlanta. A corresponding proceedings paper was submitted to the IEEE NSS conference record and to the arXiv[3].

Table 1: Comparison of material accounting for the active area of a standard PCB-based Triple-GEM detector (top) and of the foil-based EIC Forward Tracker prototype (bottom).

Detector with PCBs (e.g. CMS)	Thickness (mm)	% of Rad. Length
2 PCBs (drift and readout)	**3.180**	**3.914**
3 GEMs	**0.180**	**0.261**
Polyimide	0.150	0.051
Copper	0.030	0.210
Total		**4.175%**

Detector with foils only (EIC)	Thickness (mm)	% of Rad. Length
2 Al-Polyimide foils (gas seal)	**0.051**	**0.0184**
Polyimide	0.051	0.018
Al	0.0002	0.0004
3 GEMs	**0.180**	**0.261**
Polyimide	0.150	0.051
Copper	0.030	0.210
1 GEM as drift foil	**0.060**	**0.087**
Polyimide	0.050	0.017
Copper	0.010	0.070
Readout foil	**0.080**	**0.227**
Polyimide	0.050	0.017
Copper (15 μm each side b/c of vias)	0.030	0.210
Total		**0.593%**

1.3.3 INFN Trieste

Activity in period July 2017- December 2017

1. **Studies of novel materials for the THGEM PCB in period July 2017 - December 2017** The characterization of another novel material candidate to be used as THGEM substrate has been performed. These further studies follow the characterization of Permaglas, where Permaglas was established as a suitable material for the production of high quality THGEMs.

   THGEMs by ARLON® 25 FR (an epoxy laminate woven fiberglass reinforced, ceramic-filled composites using a non-polar, low loss, thermoset resin) have been produced and one of them has been characterized and compared with the performance of a standard THGEM by fiberglass FR4. The size and geometrical parameters of the two electron multipliers are identical: active area of 300×300 mm^2, hole diameter of 0.4 mm, hole pitch of 0.8 mm, thickness of 0.4 mm and no rim. The two multipliers have been tested by detecting X-rays from a ^{55}Fe source with effective rate of 5 kHz, in single layer configuration mounted in the same detector and using the same gas mixture. They exhibit extremely similar performance concerning gain behavior and energy resolution (Figs. 10 and 11). On the contrary, the time evolution of the gain is substantially different, indicating a slower development in the ARLON multiplier (Fig. 12). Even more remarkable is the gain variation observed for the THGEM by ARLON

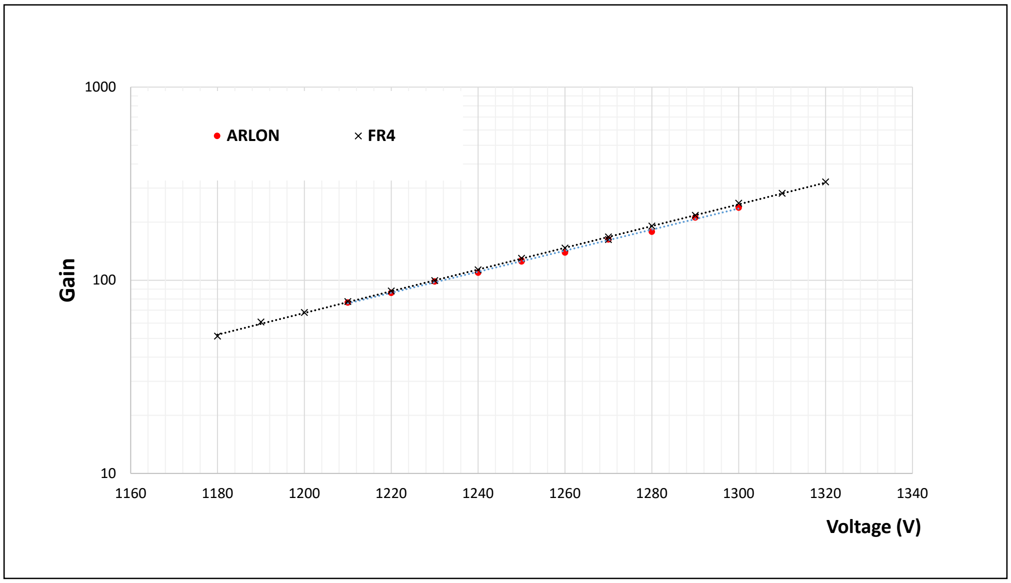

Figure 10: THGEM gain versus biasing voltage; red dots: ARLON THGEM, black crosses: FR4 THGEM.

where a dramatic persistent gain reduction is generating after several hours of illumination (Fig. 13). On the contrary, in FR4 THGEM, the gain decreased after illumination is recovered within a few days (Fig. 14). The gain evolution versus time and the extremely long recovery time after illumination indicate that ARLON is not a material suitable for THGEM production.

2. **Design, construction and first tests of the resistive MM by discrete elements with miniaturized pad-size in period July 2017 - December 2017**
   The design and construction of the hybrid MPGD-based photon detector with miniaturized pads has been completed. In this prototype the resistive MICROMEGAS has an active surface of 100×100 mm^2, while the pad-size is 3×3 mm^2 with 3.5 mm pitch, for a total number of 32×32 pads. The pads are grouped in 32×4 modular units; each unit is equipped with a connector interfacing the signal pads to the front-end electronics and a second, identical connector, providing the biasing voltage to the anode pads via protection resistors, one per pad, housed in a dedicated resistor board. Figure 15 illustrates the detector design, while the construction activity is documented in Fig. 16.

   The novel DAQ Raven system has been developed to enlarge the acquisition band width. It is entirely LabView based and decidated to data acquisition from the SRS system, where the APV25 front-end chips are used. The setting of the APV25 chips and their configuration is performed via Raven, as well as data collection and their visualization, where the channel mapping is taken into account. Raven includes several other features like pedestal subtraction and zero suppression and it is enriched by an extremely user friendly graphical interface (Fig. 17). The bandwidth obtained is the maximum compatible with the SRS architecture: in fact, Raven can transfer data up to the saturation rate of the Gigabit Ethernet when the UPD protocol with Jumbo Frame format is used, as it is the case for SRS.

   Initial tests of the prototype have been performed using only the MM multiplication stage, Ar:CO_2 = 70:30 gas mixture and illuminating the detector with an X-ray source (^{55}Fe). The MM exhibits good electrical stability up to gain-values as high as approximately 20 k (Fig. 18).

3. **Preparatory activity to study the compatibility of an innovative photocathode based on NanoDiamond particles with the operation in MPGD-based photon detectors**

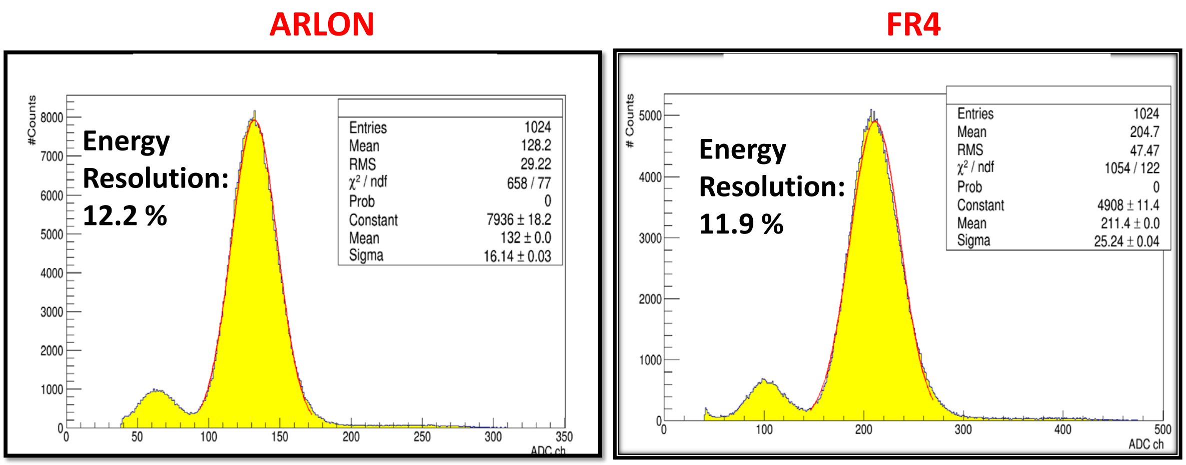

Figure 11: THGEM energy resolution estimated from the standard deviation of the main peak in the amplitude spectrum obtained detecting X-rays from a ^{55}Fe source; left: ARLON THGEM, right: FR4 THGEM.

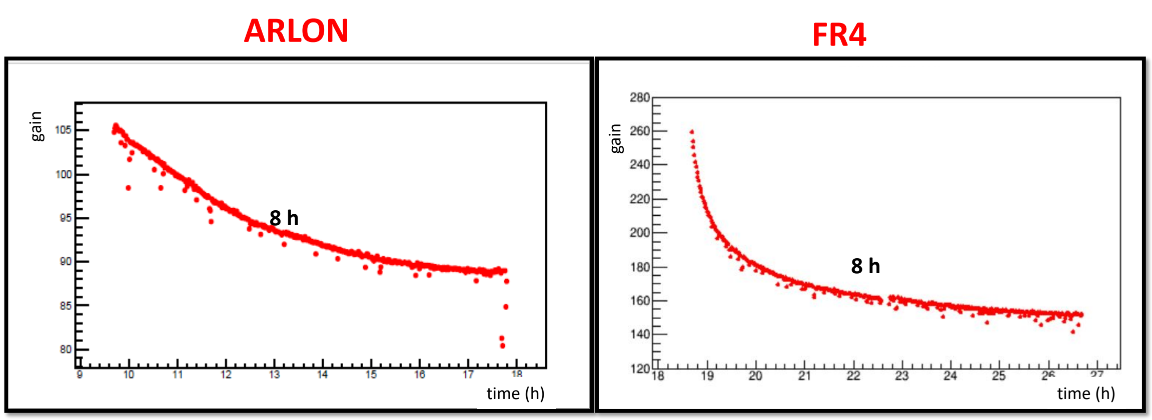

Figure 12: THGEM gain evolution versus time; left: ARLON THGEM, right: FR4 THGEM.

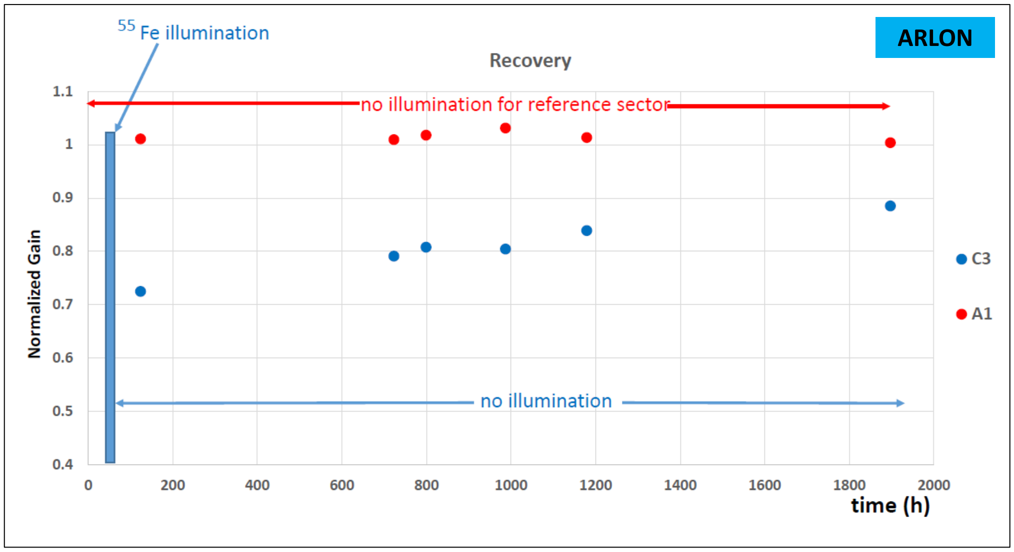

Figure 13: Gain of the Arlon THGEM measured at a specific location after illuminating it by the ^{55}Fe source and related gain evolution, compared with the gain at a non-illuminated location. The gain is normalized to the average gain allover the detector; illuminated location: C3, reference location A1.

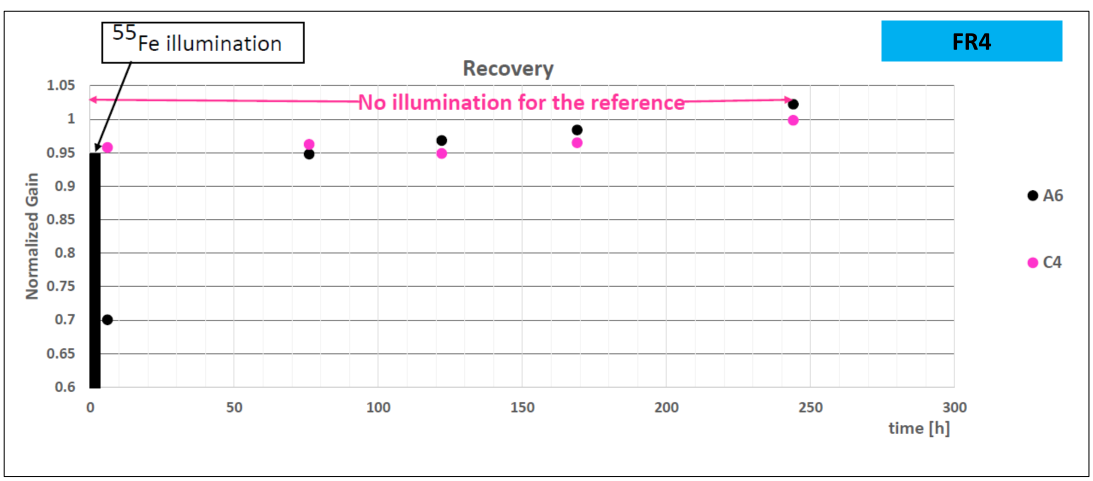

Figure 14: Gain of the FR4 THGEM measured at a specific location after illuminating it by the ^{55}Fe source and related gain evolution, compared with the gain at a non-illuminated location. The gain is normalized to the average gain allover the detector; illuminated location: A6, reference location C4.

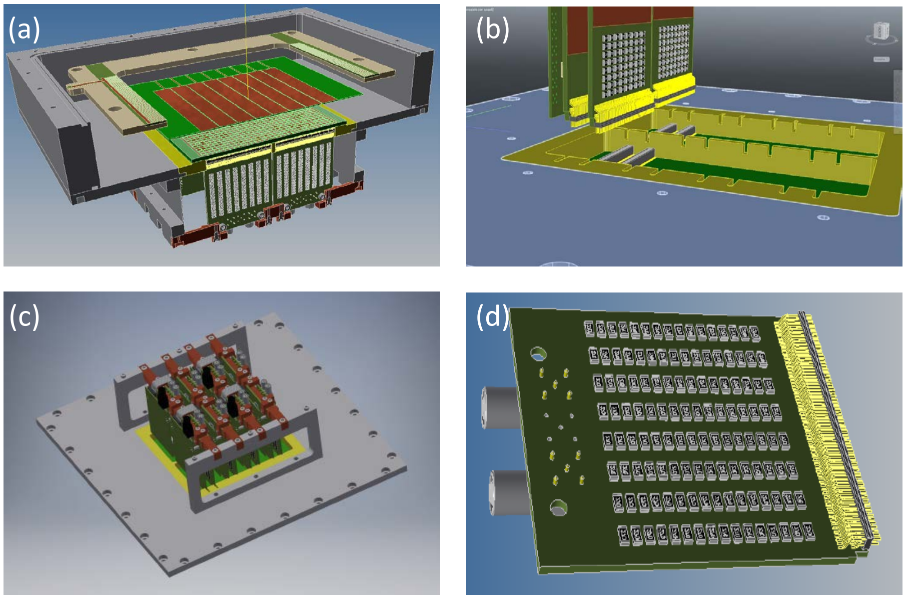

Figure 15: Prototype design. (a) Cross-section of the detector: the elements visible from top to bottom are the THGEM layers, the MM stage and the resistor cards. (b) Detector rear side: detail of the connectors and the read-out and resistor cards. (c) The rear side of the detector fully equipped. (d) The design of the resistor card.

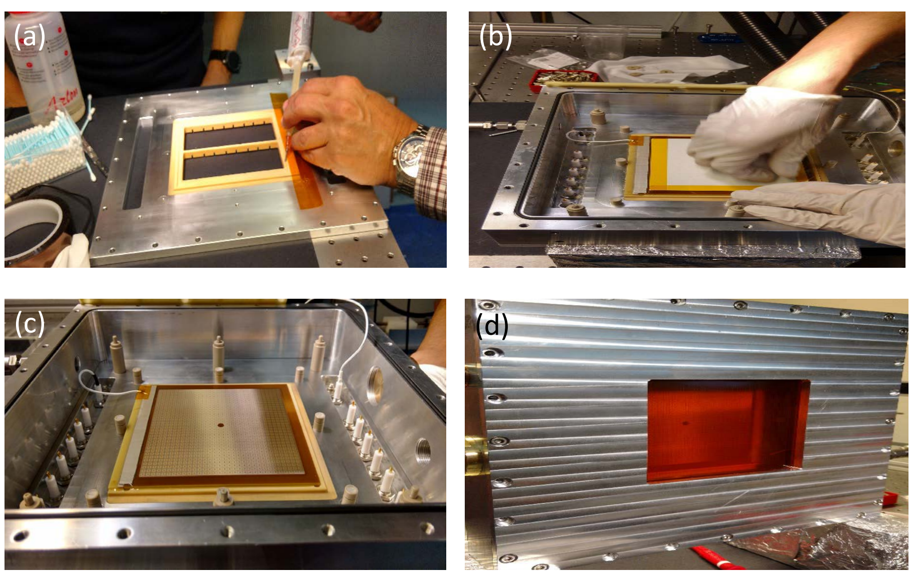

Figure 16: Prototype construction. (a) The fiberglass frame supporting the MM is glued onto the Al chamber structure. (b) The MM is glued onto the fiberglass frame. (c) The MM installed in the chamber and its power lines are visible. (d) The chamber is closed with a mylar window.

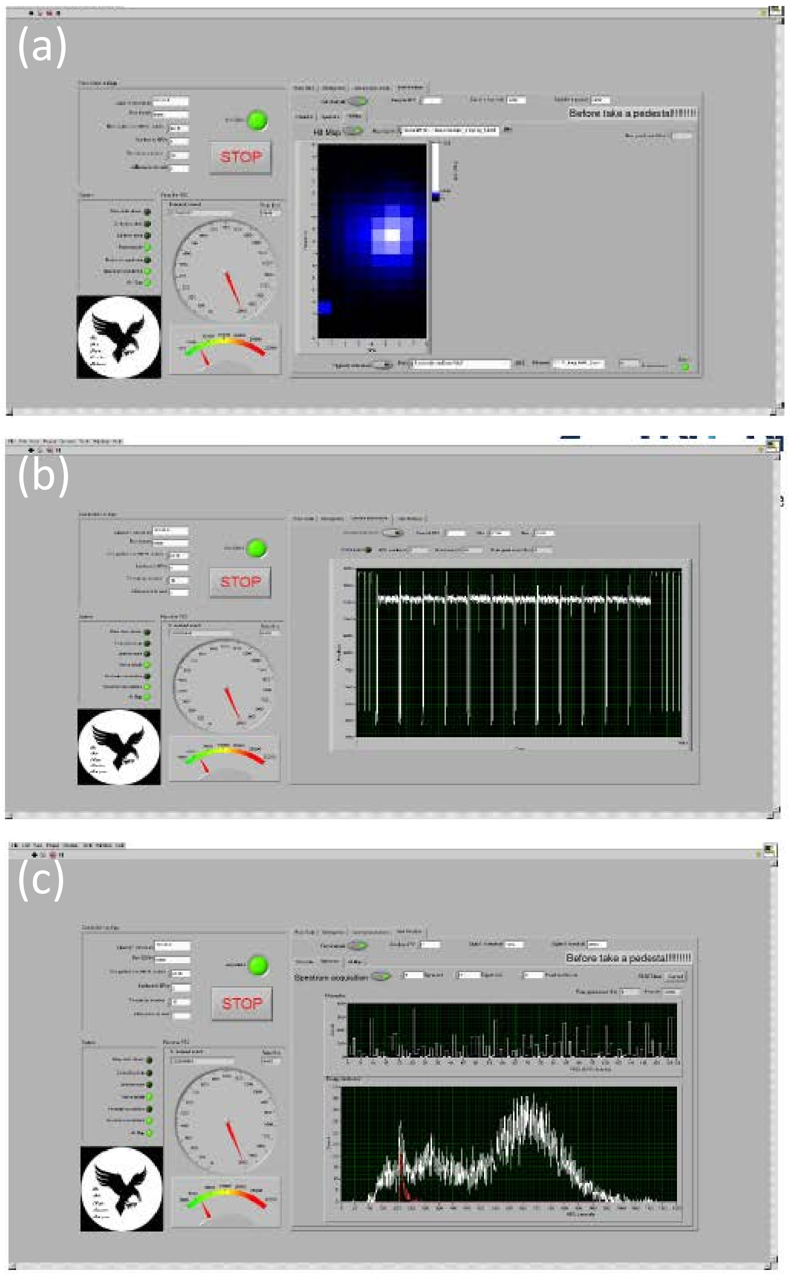

Figure 17: Raven graphical interface, data display: (a) 2D amplitude plot; (b) the amplitude measured in each of the 128 channels of an APV25 chip is displayed for each time clock (40 MHz); (c) the amplitude spectrum of the maximum amplitude in each read-out cycle.

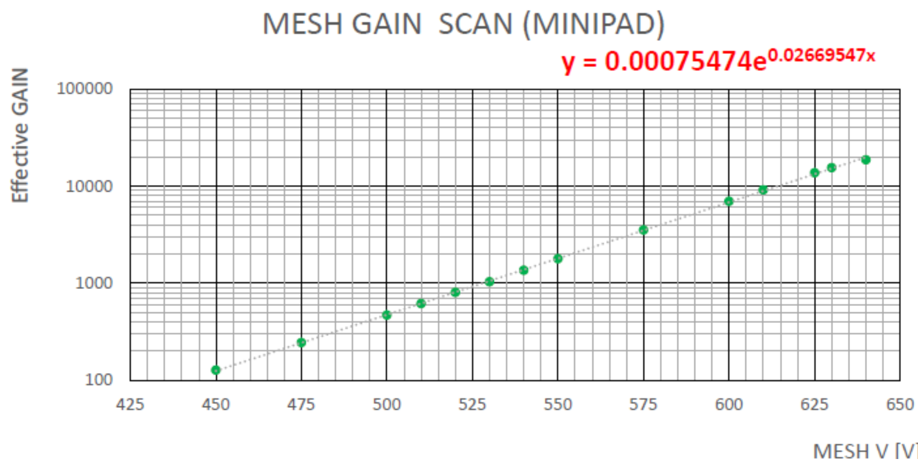

Figure 18: Effective gain of the MM stage of the prototype with miniaturized pad-size versus the applied biasing voltage.

The activity planned in year 2018 includes a very basic set of studies in order to understand if there is any evident stopping point that prevents the use of ND photocathodes in gaseous detectors. The foreseen studies include:

- comparing the quantum efficiency of photocathode samples in vacuum and in different gaseous atmospheres;
- checking if the ND photocathode releases dust particles in a gaseous atmosphere;
- realizing and characterizing a photon detector prototype with an ND photocathode using as substrate a THGEM.

A meeting between the INFN group in Trieste and the colleagues from INFN Bari, who introduced the novel ND photocathodes, took place in Trieste in December 2017. The planning and methodology for the foreseen studies has been discussed in detail and the production of a few photocathode samples dedicated to these exercises has been scheduled. A setup already available at INFN, Sezione di Bari, will be used for the QE measurements.

The activity related to further development of MPGD-based photon detectors was started in 2017 and, therefore, the outcomes are not yet mature enough for contributions to conferences and for publications.

1.3.4 Stony Brook University

We have started to install the equipment for mirror evaporation. We are preparing to get the clean room in workable condition so that the evaporator can be accordingly operated.

Publication of results:

As mentioned in the BNL section,

1. We are co-authors on a manuscript entitled: “Beam Test Results from a GEM-based Combination TPC-Cherenkov Detector” which is almost complete and will be submitted to the IEEE journal, Transaction on Nuclear Science within the next few months.

2. We are co-authors on a manuscript entitled: “Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors” which summarizes the results from our latest R&D efforts with zigzag geometries and was very recently submitted to the IEEE journal, Transaction on Nuclear Science.

1.3.5 University of Virginia

Full size EIC Forward Tracker (EIC-FT) GEM prototype
We have received the 2D U-V strips readout board from CERN PCB workshop as well as the mechanical

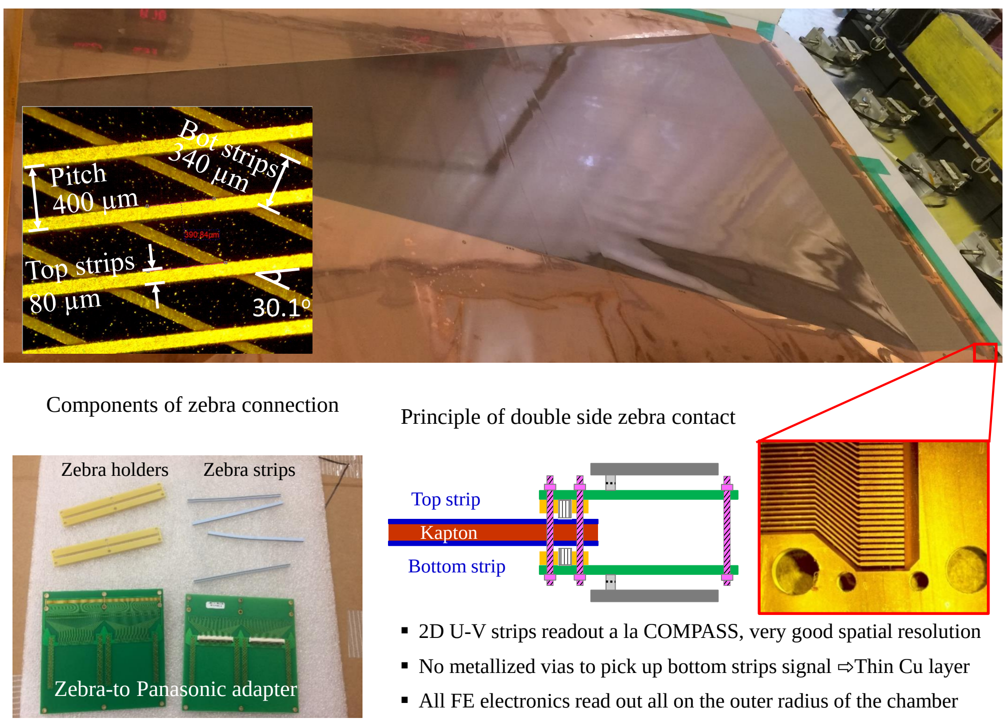

Figure 19: 2D U-V strips readout for UVa forward GEM tracker prototype. Components for the double-sided zebra connection are also shown.

parts needed for the zebra connection (Fig. 19) which consist of 10 zebra-to-Panasonic adapter boards and 10 zebra holder pieces. The zebra strips were procured from Fujipoly Company. The only parts currently missing to start the assembly are the GEM support frames. We are working on some modification of the original frame design to reduce the production cost. The modification mainly affect the 4 outer frames that defines the front and back gas window volume of the chamber. These frames do no require precision machining of 300 μm spacers and therefore can be produced locally in our machine chop. The design modification is almost completed and we are about to place the order before the end of the year. We are also working on refurbishing the exiting mechanical stretcher and associated assembly plates that we used in the past for PRad GEMs in order for them to be re-used for the assembly of the EIC-FT GEM prototype.

Study of the Chromium GEM (Cr-GEM) chamber

Aging test of Cr-GEM proto II with x-ray

We are still pursuing the aging studies of Cr-GEM proto II with the x-ray setup as reported in the previous progress report. The main difference between Cr-GEM proto I and proto II is the replacement of the 3rd GEM (Cr-GEM1) foil which was damaged after the intense x-ray test of proto I was replaced by a new one (Cr-GEM2). The chamber (proto II) has been continuously exposed to x-ray at relatively high rate (estimated to be about 1   3 MHz / cm^2) for about 3 months with the chamber operating at a low and high gain of about 1×10^3 to 5×10^3 which are equivalent to the operating gain of about 1×10^4 to 5×10^4 for MIP particle. We did not observed any long term degradation of the detector performances performances

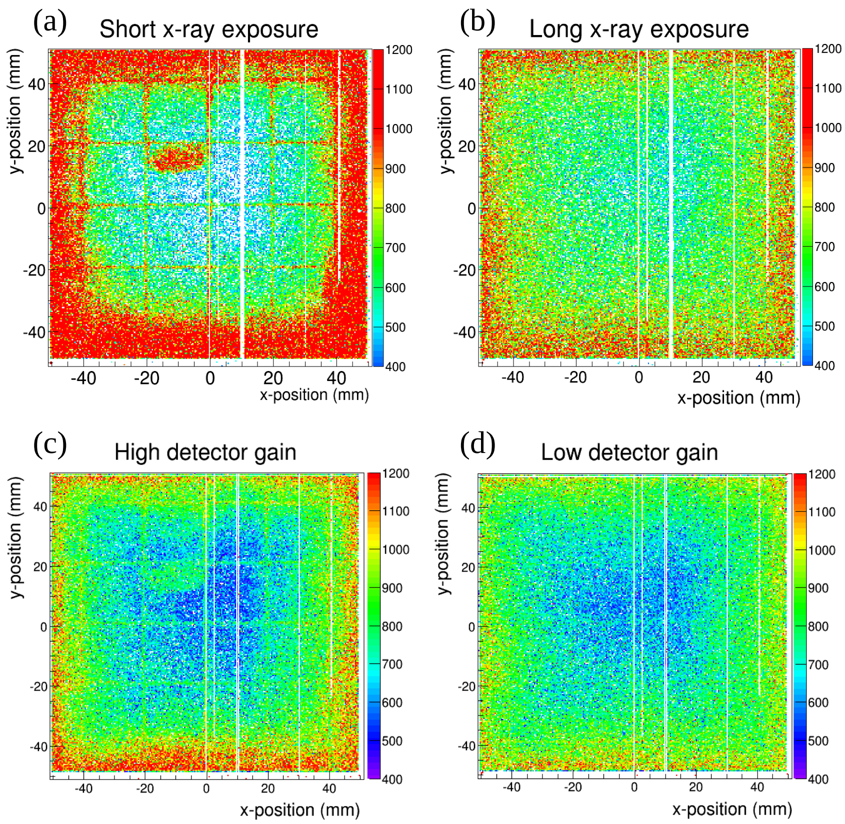

Figure 20: Effect of charging up of Cr-GEM with conductive Cu grid: at the beginning of x-ray exposure *(a)*; or at high gain *(c)*; smooth gain variation after long exposure *(b)* and at lower (nominal) gain *(d)*

during the whole run. The average ADC amplitude distribution which measure the relative gain uniformity are shown on the plots of Fig. 20 in different test conditions. The overall continuous gain variation from the edge of the detector to the center seen on Fig.20 b and Fig.20 d is explained by the fact that the flexible readout strips board for this prototype was bent under the Ar-CO_2 gas pressure during the x-ray tests. However, we have observed some unexplained charging up effect around the Cu grid in the active area that was left to ensure electrical conductivity. At the beginning of x-ray exposure (even at the lower gain of 1×10^3) or when the chamber was operating at higher gain of 5×10^3, the average ADC amplitude was found to be significantly higher (2 to 3 times) around the Cu-grid than elsewhere in the detector active area (Fig.20 a and Fig.20 c). After about 24 hours of continuous x-ray exposure at the lower gain of 1×10^3, a smooth gain uniformity is restored and the Cu-grid is no longer distinguishable (Fig.20 b and Fig.20 d). We were able to reproduce the behavior of the detector several times which led us to conclude that the charging up

effect was real but does not lead to a permanent damage of the detector or modification of its performance.

Optical Microscope scanning of Cr-GEM foils
We analyzed two Cr-GEM foils at the GEM CCD scanner facility at Temple U. The GEM CCD scanner,

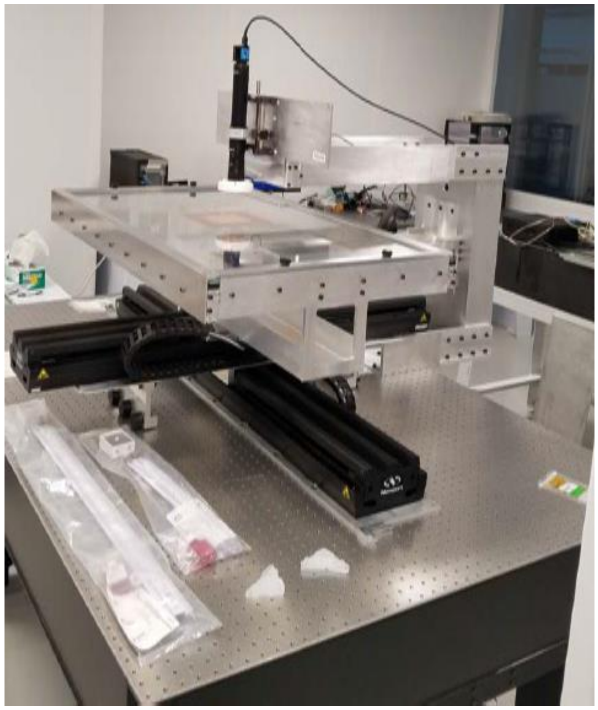

Figure 21: GEM CCD Scanner at Temple U.

developed by Prof. B. Surrow and Dr. M. Posik allow the optical scanning of large GEM foil in order to study of GEM holes parameters such as inner, outer hole and pitch geometry and uniformity, as well as fabrication defects over large area. We scanned our damaged foil (Cr-GEM1 foil) used in the intense x-ray test of proto I as well as a good Cr-GEM foil. Figure 21 shows a picture of the GEM CCD Scanner at Temple U. The CCD scan setup was originally calibrated to scan standard GEM foil for which the $5\mu m$ Cu layer on each side of the foil would effectively block the transmission of the light placed below the foil and that provides the ideal contrast for a good imaging of the outer holes of the GEM foil. However with a Cr-GEM foil with only a few hundreds nm thick Chromium layer, the transmission of the light from the back prevent a good resolution imaging of the outer holes. Therefore during the scanning of the Cr-GEM foils, we were only able to correctly measure the inner hole diameter as well as the hole pitch. The plots of Figure 22 show the distributions of the inner hole diameter and pitch size for the two Cr-GEM foils. The mean value of these distributions represents inner hole diameter equal to $49.3\mu m$ for the good foil (plot (a)) and $54.3\mu m$ for the damaged Cr-GEM foil (plot (b)). The narrow distribution with a standard deviation less than $1.4\mu m$, is a good indication that there was no etching of the Kapton that occurs during the high rate x-ray exposure that ultimately leads to the degradation of Cr-GEM1. The optical scan measurement is an important because it provides the information on the Cr-GEM holes over the full area of the damaged Cr-GEM1 foil in addition to the local inspection of the GEM hole that we obtained by the SEM measurement described in the following section.

SEM measurement of Cr-GEM foils
After the optical scan measurements performed at Temple U. we sent samples from 3 Cr-GEM foils that were all intensively used in the two Cr-GEM prototypes and one standard GEM with Cu electrode to CERN

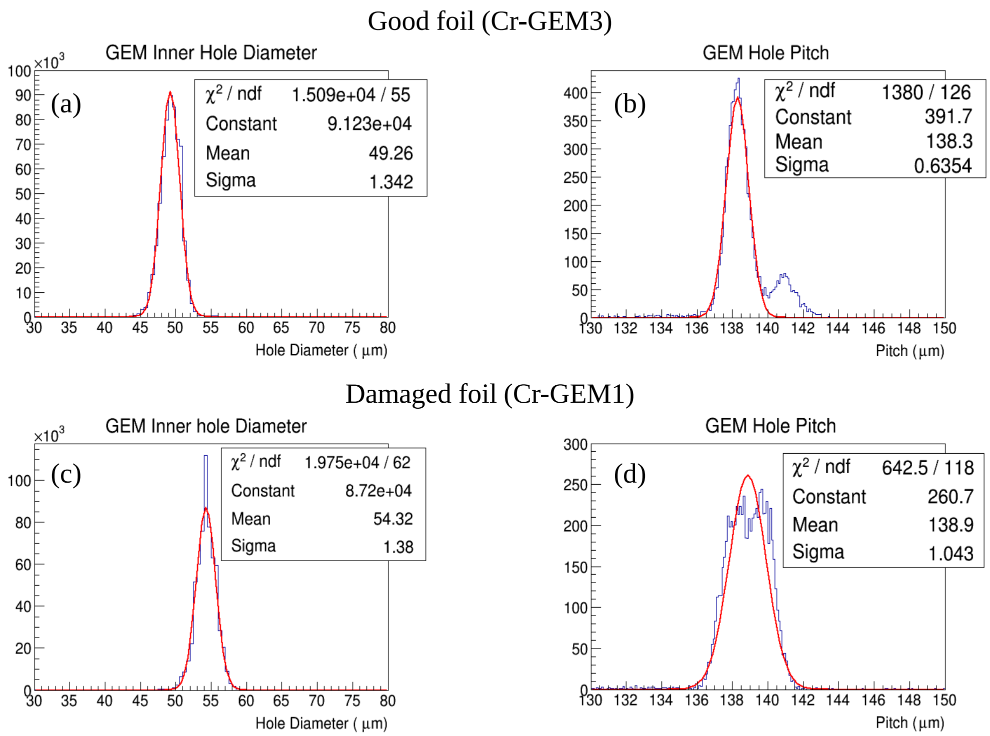

Figure 22: Inner hole and pitch size distribution for the good Cr-GEM3 *(a) and (b)* respectively and damaged CrGEM foil *(c) and (d)* respectively.

for SEM analysis of the holes properties and a more detailed inspection of the damaged foil from the first prototype. The SEM measurement were performed by Dr Alexander Lunt from CERN Material, Metrology and NDT group (CERN EN/MME/MM) and with the logistic and administrative support of Eraldo Oliveri of the RD51 group at CERN. Below is the list of the samples prepared for the SEM analysis

- **Sample Cr-GEM1:** from the damaged foil used as third amplification GEM in proto I and which was exposed to the high rate and operated at high gain. The visual inspection of this foil before the SEM shows that the Chromium layer at the bottom side of the foil has vanished from the entire area while the top side of the foil seems intact.
- **Sample Cr-GEM2:** from the Cr-GEM used as the third amplification GEM used in proto II as replacement of the damaged Cr-GEM1. There were no clear indication in the data of damages from this foil during the 3 month long of continuous x-ray exposure at a low and high gain but at relatively high x-ray flux. However a visual inspection after the chamber was opened shows some hints of Chromium "evaporation" on the bottom side of this foil similar to Cr-GEM1. Though, the damages were far less pronounced than for Cr-GEM1. Top side once again did not show any degradation
- **Sample Cr-GEM3:** from a foil used as second amplification Cr-GEM foil for both proto I and proto II and therefore was exposed to the high rate / high gain campaign of proto I as well as the long term exposure campaign of proto II. A visual inspection of this foil before the SEM measurement did not reveal any damage or apparent problem in either side of the foil.
- **Sample std-GEM:** from a standard Cu-GEM foil with 5 μm Cu electrode on both top and bottom side used just as a reference.

The pictures on Figure 23 show the cross section of a standard GEM with 5 μm Copper layer (left) and

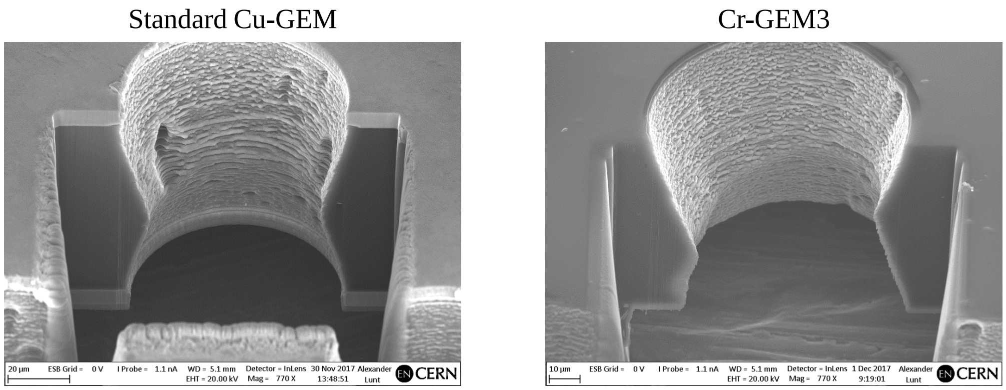

Figure 23: Cross section of: standard GEM *(left)* and a Chromium GEM *(right)*

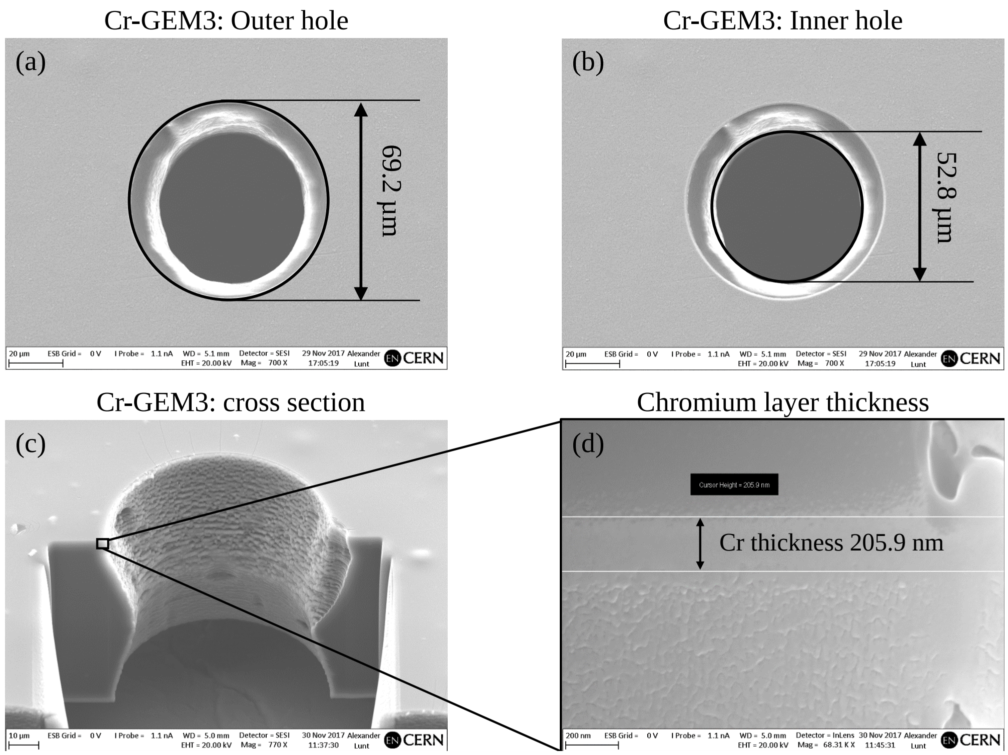

Figure 24: Geometry of the Cr-GEM hole. Expected diameter of the outer (a) and inner (b) hole; Chromium layer thickness (d)

a Cr-GEM hole (right) with similar bi-conical shape of the polyimide and with a much thinner Chromium layer. The basic geometric parameters of the Cr-GEM are displayed on Figure 24 and the thickness of the Chromium layer has been measured to be between 200 and 300 nm for different samples which is significantly higher to the expected value around 100 nm but still more than an order of magnitude thinner than a Cu-GEM copper layer. Figure 25 shows the SEM images of the top and bottom side (pictures (a) and (b)) of the damaged foil (Cr-GEM1). As we previously already observed from visual inspection, the images of the top side (pictures (c) and (e)) are of high quality with the holes dimensions and configuration very similar to a normal GEM foil. (Pictures (d) and (f)) for the bottom side of the foil where the Chromium is suspected to have been etched out, show SEM images that appear severely distorted. Similar effect can

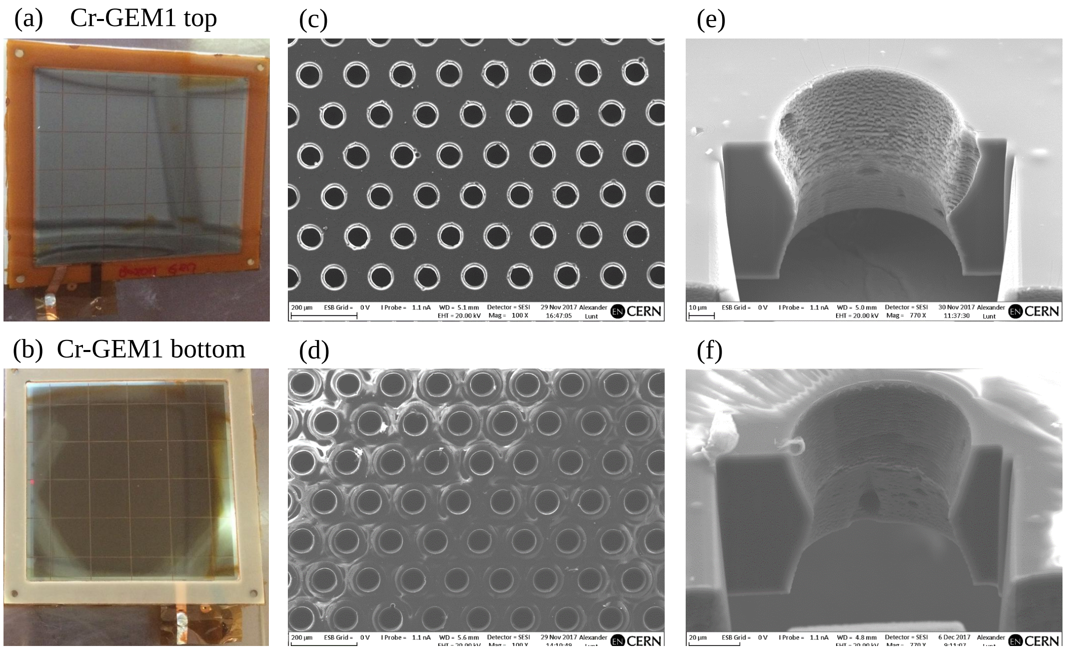

Figure 25: SEM images of both top and bottom electrode *(a) and (b)* of damaged foil (Cr-GEM1). For the top electrode, the images are of good quality *(c) and (e)*. For the bottom electrode, the images shows poor resolution *(d) and (f)* which is an indication that the SEM was performed on a non conductive surface.

be seen on the right picture of Figure 26 for the Cr-GEM2 foil used as third GEM in proto II, however the damages are far less severe than than for Cr-GEM1 (on the left picture) and seems more localized around the holes as opposed to the Cr-GEM1 where it spreads over the entire active area. The less severe distortions indicated that the damages are limited which would explain why we did not observed any apparent effect on the detector performances during the x-ray tests. It seems like the overall structure of the GEM foil seems to be preserved with only probably Chromium slightly etched out around the holes. These are just preliminary interpretation of the measurements and we are still analyzing the data to have a better understanding of the Chromium evaporation effect. It is a very well documented phenomenon that SEM measurement performed on a non conductive with high beam intensity lead to a charging up effect taking place on the surface under test. The electrostatic charges are trapped inside the dielectric material lead to a modification of the electric field at the surface that deflects the normal path of the secondary electrons producing the SEM image. This is the explanation of the distorted images seen on picture (d,f) of Figures 25 and as well as pictures (a,b,c) of figure 26. The poor quality images are an indication that the metallic layer (Chromium) has effectively disappeared (evaporated) on the bottom side of Cr-GEM1 and at a lesser degree around the holes at the bottom side of Cr-GEM2. A common solution to restore a good SEM image is to coat the surface to be probed with a thin conductive layer (5 nm of gold, palladium etc..) which is grounded to help evacuate the unwanted electrostatic charges. Figure 26 shows a zoomed view of the SEM image of a Cr-GEM1 hole at the bottom side before (c) and after (d) the coating with the conductive layer. The improvement of the image resolution on picture (d) when the coating is applied is clearly demonstrated here and is a confirmation of the hypothesis of the Chromium evaporation

The SEM measurement perfectly validate our initial hypothesis that the damages caused by high rate x-ray exposure at high gain for a triple Cr-GEM detector only affect to the bottom side of the third amplification Cr-GEM foil and lead to the "evaporation" of the Cr layer with no etching of the polyimide. The top layer of this foil seems to be not affected and the first and second amplification Cr-GEM foils are left untouched.

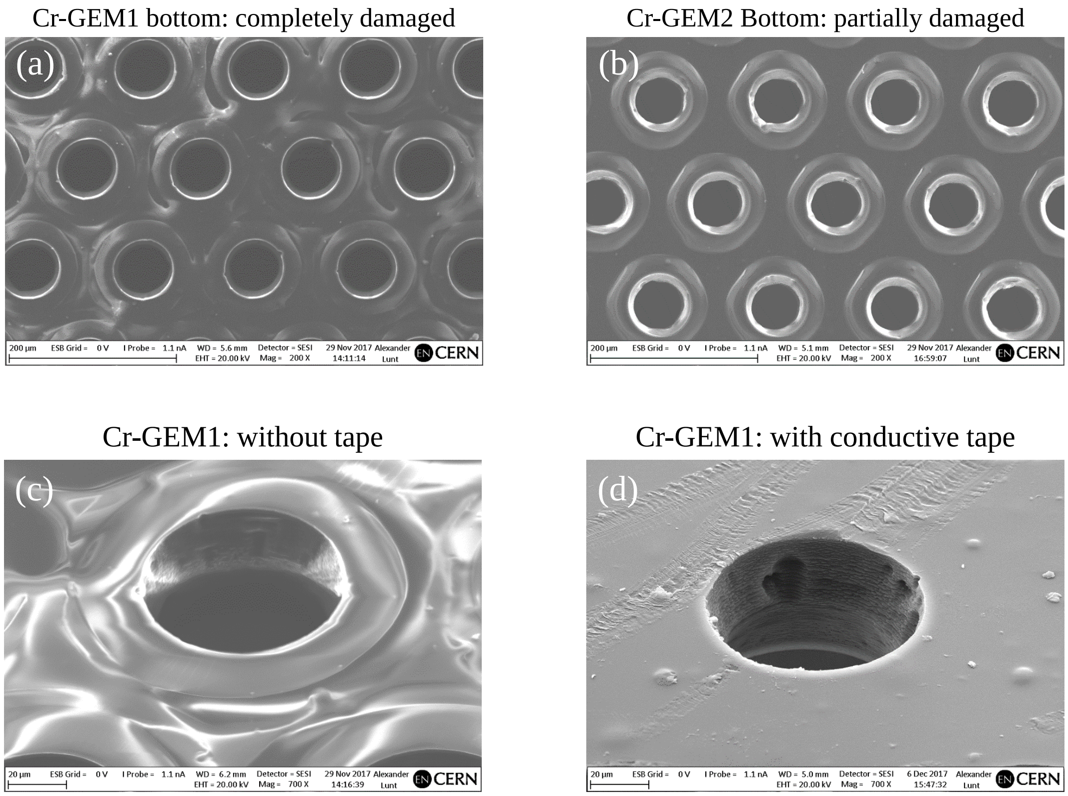

Figure 26: SEM images of a GEM hole at the bottom electrode of samples Cr-GEM1 *(a)*, and Cr-GEM2 *(b)*. Zoom view of one Cr-GEM1 hole before *(c)* and after *(d)* after coating the sample with conductive tape.

Conference presentations
K. Gnanvo presented the status of UVa R&D for the EIC forward GEM Tracker at the MPGD2017 conference in Temple U. and more specifically the latest results on Chromium GEM development at the RD51 Collaboration mini week at CERN in December 2017.

1.3.6 Yale University

1. Multi-element stacked gated grid.

MWPC plus 3 additional wire plains were prepared and tested to check that HV configurations can be found to get both options: high efficiency electron transmission (open gate) and IBF practically zero (closed gate). The source of positive ions from gas amplification step with good timing parameters (fast start and stop) was established using UV-diode and Al cathode as a source of primary electrons. We tested different options to prepare fast HV switches (-300 V to -600 V and -300 V to 0 V; with switching time smaller than 1 μ s).

1.4 What was not achieved, why not and what will be done to correct?

1.4.1 Brookhaven National Lab

1. ***GEM studies of TPC gas mixtures***: Though we verified our older measurements of the gain stability and energy resolution of the Ne/CF4 (90/10) mixture, we have not yet pursued other studies of TPC gases. This is because the detector setups required for many of the tests in question still need

to be built before the aforementioned gas studies can be carried out. However, we have purchased new mass flow controllers for these tests and have designed and built the appropriate gas handing system which incorporates the new MFC's. We have also procured high purity gas bottles for future tests, but have not yet received the 12 channel picoammeter module required for some of these tests. Ultimately, we now anticipate that a substantial portion of these tests will be carried out in the coming 6-12 months.

2. ***FEE using SAMPA***: Due to some delays in receiving the SAMPA electronics and the need to commission their use by experts, we have not yet tested the SAMPA electronics in our lab. However, our colleagues have begun some very preliminary tests of the SAMPA chips and have successfully been able to read them out using in-house DAQ systems. So far only pulser data has been recorded, but the next step is to connect the SAMPA electronics to a GEM detector in our lab and read out real signals generated by the detector. We anticipate that this should happen over the next few months.

1.4.2 Florida Tech

As we are still in the process of finalizing the procurement of all detector components, we did not yet assemble the detector and we did not yet put it through any quality control tests.

1.4.3 INFN Trieste

The activity is progressing according to the planning.

1.4.4 Stony Brook University

The installation and first operation of the equipment in the evaporator has not been finalized yet. The installation was delayed due to unexpected working conditions in the location of the evaporator. We are working hard to get the proper working conditions in place.

The studies for a TPC in an EIC detector have not been started because funding did not yet arrive.

1.4.5 University of Virginia

The assembly of the large GEM prototype has not started yet. The cost of the GEM support frames with ultra thin spacers remains a big issue. The quote that we received from the Belgian company RESARM for production of the set of 8 frames, is significantly higher than what was planned in our original budget. Therefore we decided to modify the current design to have half of the frames produced locally at a lower cost. These low cost frames are for the support of the outer layers of the prototype such as the entrance window foils and as such do not require spacer grids.
We expect to be able to finalize the design work by mid December 2017 and to place the order before the end of the year. This would delay the construction and preliminary tests of the prototype by a couple of months but we still expect the prototype to be ready for the Test beam at Fermilab this summer.

1.4.6 Yale University

We are still tuning the HV switches to achieve $\sim$ 1s or less switching time. In combination with pico-ampermeters we will measure the crucial parameter: how fast positive ions can be collected in such multi gate structure to compare with simulation results and measure how much dead time is required to achieve low IBF Currently we have a prototype HV switch unit that looks promising. We need to check the performance in detail to assure it gives the needed timing (switch in less than 1 μs). We then need to prepare 3 HV fast switchers to operate the stacked grid in various configurations..

2 Future

2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

2.1.1 Brookhaven National Lab

1. ***Zigzag pad development***: We plan to continue the development and optimization of the zigzag pads, with a focus on pursuing more accurate fabrication methods. In particular, after speaking with several experts, we have learned that the laser ablation process is available at reasonable cost, which seems to be among the most accurate fabrication techniques available on the market. We would like to iterate on several PCB's made using this process which provides smaller gaps between zigzag pads and thus increased pad overlap, for improved performance. However, we have not yet fully ruled out the use of high precision chemical etching for the production of new PCB's, though this process comes at a premium in cost.

   In parallel we also plan to pursue more simulation work to fundamentally explain how charge is shared among neighboring zigzag pads. The new simulations will include comprehensive electric field calculations to accurately model the transport of individual electrons from the induction gap to the collection electrodes. The insights gained from such realistic models will inform and refine our zigzag designs further and will bring us a step closer to realizing the optimum design for reconstructing tracks within a TPC.

2. ***Beam test with multi-zigzag PCB***: A mini-drift GEM detector equipped with a multi-zigzag readout will be placed in the primary 120GeV beam at the Fermilab test beam facility in March 2018. It will be positioned just downstream of a high precision silicon tracking telescope, which has a projected track resolution at the location of the GEM detector of about 17μm. Using this detector, we plan to study a multitude of zigzag geometries in a single board using the relatively high rate particles of the beam for the purpose of identifying the optimal zigzag geometry for a given detector setup. The parameters that define the various geometries contained within this board span an interesting range of the parameter space. Thus by scanning the board with the particle beam, we hope to reveal behavioral trends as a function of these parameters. Time permitting, we will conclude our tests by rotating the detector stand such that the beam enters the detector at certain angles over selected zigzag geometries for the purpose of reconstructing ˜1.5cm ”track-lets” from the timing information derived from the pad signals [34].

   The full data set from the beam test will contain very high precision positional information for reference tracks from the silicon telescope, corresponding to points uniformly spread across varying zigzag geometries. This will allow for numerous studies that can precisely probe the fine structure of each zigzag, beyond what is possible using our in-lab x-ray scans. Among the studies that may be made, we can study the zigzag periodicity without having to look at the integrated response along the slit width of the in-lab x-ray collimator. In addition, the precision of the silicon telescope is negligible compared to the calculated resolution of the GEM detector, unlike the truth position of x-ray hits which include an uncertainty approaching 40-50μm due to the width of the x-ray collimation. In the latter case, this may be problematic since the uncertainty may be a significant contributor to the overall calculated resolution.

3. ***Measurements with GEM-based cosmic ray telescope***: We plan to use the cosmic ray telescope for the purpose of reconstructing cosmic tracks to high precision. These high precision tracks will be used as a reference to compare to tracks reconstructed using a detector under test (DUT), such as a minidrift GEM detector [34] equipped with a zigzag PCB. This will provide a measure of the position resolution for each PCB using true particle tracks to compliment the resolution as determined from the x-ray scans described earlier. Since it is preferable for the reference track to contribute a negligible width for the residual distribution (calculated as the difference between the reference hit position and the DUT reconstructed position), every attempt will be made to make the reference track as precise

as possible. We estimate the position resolution for the reference track of the 4-layer telescope to be better than 30μm, determined by the resolution per layer over the square of the number of layers. This assumes that the position resolution of each layer is better than 60μm, which is the typical resolution of a 3-GEM detector with COMPASS readout for normally incident tracks.

4. ***GEM Studies using TPC gas mixtures in a compact TPC prototype***: We plan to continue doing GEM studies using gas mixtures favorable for a TPC in a compact prototype TPC comprising a 10cm x 10cm x 10cm field cage coupled to a 10cm x 10cm 4-GEM detector. Among the gas characteristics mentioned above, we plan to pay particular attention to ways of maximizing the electron extraction and collection efficiencies and reducing ion back-flow by exploring the electric field ratios in neighboring gaps between GEMs, while maintaining adequate energy resolution. In addition, such a compact TPC may be used to further characterize zigzag PCB's by reconstructing longer particle tracks than what can be reconstructed in a minidrift arrangement (ie, ˜10cm tracks as opposed to ˜1.5cm tracks). At this point we anticipate to have the detector operational after the March beam test in time to test it with the next iteration zigzag PCB in the lab and possibly at a planned beam test at the Fermilab test beam facility in July 2018.

2018 Milestones:

- Early January: Production of mulit-zigzag PCB using laser ablation process
- Mid. January: In-lab partial x-ray scan of multi-zigzag PCB
- End of February – End of March: FNAL beam test to study zigzag geometries contained in multi-zigzag PCB
- April – July: Analysis of beam test data and studies with compact TPC prototype
- Early July: 2nd beam test with next iteration zigzag PCB + compact TPC (tentative)

2.1.2 Florida Tech

Forward Tracker Prototype: Our main goal for the next six months is to assemble the new one-meter-long FT GEM detector with zigzag readout and to put it through a battery of quality control tests. These tests will be modeled on the QC for large GEM detectors that we are performing for the CMS forward muon upgrade. We will work closely with the BNL and UVa groups to prepare for a joint forward tracker beam test at the Fermilab test beam facility in summer 2018. We also hope to procure a small (10×10 cm^2) resistive micro-well detector from CERN during the next period to begin some basic R&D on this detector technology for fast tracking in the barrel region of the EIC detector.

EIC Simulations: We have identified an undergraduate student, Matt Bomberger, to begin work on EIC simulations for investigating the impact that material budgets in the forward and backward regions will have on the overall EIC detector performance. In the next six months, Matt will familiarize himself with the EICroot simulation framework. He will first be supported remotely by Alexander Kiselev from the BNL group. We then plan to send Matt to BNL in May or June to spend some time working directly with Alexander.

Milestones for the first half of 2018 (next reporting period):

- February 2018 - One-meter forward tracker prototype fully assembled
- April 2018 - Quality control with X-rays completed
- June 2018 - EIC simulation running at Florida Tech
- July 2018 - Beam test at Fermilab

TASK no	TASK	FY 2017				FY 2018				FY 2019				> FY 2019			
		1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter	2nd quarter	3rd quarter	4th quarter
1	test of novel materials for THGEM substrate	■	■	■	■	■	■										
2	resistive MM by discrete elements with miniaturized pad size			■	■	■	■	■	■								
3	preliminary studies towards a gaseous photon detector with CD photocathode					■	■	■	■								
4	further studies towards a gaseous photon detector with CD photocathode, IF PRELIMINARY STUDIES PROMISING									■	■	■	■				
5	comparison of THGEM vs GEM photocathodes													■	■	■	■
6	enhancement of the IFB suppression in hybrid MPGDs													■	■	■	■
7	operation of hybrid MPGDs (THGEMs + MM) in fluorocarbon-rich gas mixtures													■	■	■	■

Figure 27: Time-lines of the R&D activity "Further development of hybrid MPGDs for single photon detection synergistic to TPC read-out sensors.

2.1.3 INFN Trieste

The whole R&D project develops over several years and the overall time-lines are presented in Fig. 27. According to the planning, two activities will be pursued in 2018.

1. The laboratory studies of the novel prototype of **resistive MM by discrete elements with miniaturized pad-size**, just started in December 2017, will be continued. In particular, after the detailed characterization of the MM stage, two THGEM layers will be added to form the hybrid photon detector architecture and the characterization studies will be repeated using the complete detector. In parallel, a set-up adequate for test beam studies will be realized to make possible the characterization of the detector performance at a test beam in Autumn 2018.
2. The initial studies to understand the compatibility of an **innovative photocathode based on NanoDiamond (ND) particles** with the operation in gaseous detectors and, in particular, in MPGD-based photon detectors, have been detailed and planned. The activity includes the comparative measurement of the quantum efficiency in vacuum and in various gas atmospheres, the compatibility of the ND photocathodes with the operation in gases in term of dust release (if any) and the overall performance of a MPGD when equipped with the ND photocathode, the initial characterization of a MPGD-based photon detector with ND photocathode. More information concerning the ND photocathode, including also the motivations for these studies, can be found in Sec. 2.3.3.

Following the activity planning, the **milestones for 2018** are:

- September 2018: The completion of the laboratory characterization of the photon detector with miniaturized pad-size.
- September 2018: The performance of the tests to establish the compatibility of the ND photocathodes with the operation of MPGD-based photon detectors.

2.1.4 Stony Brook University

We are planning to start up the IBF measurements as soon as we receive the requested funding and have the needed equipment in house. We anticipate to construct new IBF-reducing structures and investigate their performance in a test-beam campaign.

The installation and operation of the deposition unit within the SBU evaporator was expected to be finalized at this time. However, as mentioned in the previous section this task could not yet be done. We are expecting to be in the conditions the coming semester so that the installation can be finished.

2018 milestones:

- January - February 2018: Installation of evaporator equipment
- March - April 2018: Test of evaporator equipment
- May - June 2018: Performance tests of new IBF-reducing structures
- July 2018: Beam test at Fermilab

2.1.5 University of Virginia

The main goals for the next six months are:

- To procure all needed GEM support frames and assemble of the full size EIC-FT GEM prototype with the new U-V strips readout pattern and double-sided zebra connection scheme. Once the assembly completed, we plan to thoroughly test the prototype in our lab with cosmics, x-ray and Sr^{90} sources and prepare for the joint forward tracker test beam with FIT, BNL and Temple U. groups at the Fermilab in summer 2018.
- We will pursued the basic studies of Cr-GEM with our existing prototype and will start drafting a paper on our results for peer-reviewed publication in NIMA or TNS journal.
- Similarly to FIT, we are also planning to acquire a small μ-RWELL detector with 2D COMPASS-like readout from CERN and start some basic R&D on this new technology that we view as a strong candidate for the fast tracking device in the barrel region of the EIC detector.
- Our graduate student, Siyu Jian has committed to participate to the EIC R&D effort and work on simulations, together with FIT student, to study the impact that EIC-FT GEM material budgets on the EIC overall performance in the forward and backward regions and specially in far forward region where the ultra light Cr-GEM detector can be used to in addition to the MAPS to provide fast tracking information. Siyu has already started with the EICroot simulation framework. He will for now work remotely with the assistance of Alexander Kiselev from the BNL group and later in Spring 2018 will be sent to BNL for a couple of weeks to work directly with Alexander and complete the simulation work.

2018 milestones:

- March - April 2018: Assembly of EIC-FT GEM prototype
- May - June 2018: Performance tests with Cosmic, X-rays, Sr^{90} sources
- July 2018: Beam test at Fermilab

2.1.6 Yale University

Our plan is to finish R&D activity mentioned above and prepare the publication.

2.2 What are the critical issues?

2.2.1 Brookhaven National Lab

1. ***Laser Etched zigzag PCB's***: In order to procure zigzag PCB's which precisely reproduce our designs we would like to purchase new zigzag PCB's fabricated using the laser etching process described above, which promises to deliver precision etching far superior to traditional chemical etching, at a reasonable cost.
2. ***PicoLogic Pico-ammeters (Zagreb, Croatia)***: In order to perform some of the GEM studies described, we must purchase a set of compact pico-ammeters that are able to be floated to the high voltages applied to each GEM electrode. The pico-ammeters are also fully programmable in terms of setting parameters like the integration time, and the number of averaged samples, etc., which are necessary features for our R&D program.

2.2.2 Florida Tech

The departure of our post-doc Aiwu Zhang in Dec 2016 has severely slowed down progress. While our undergraduates are doing a fine job and are very enthusiastic about building the new prototype detector, they have limited availability and experience.

2.2.3 INFN Trieste

No critical issue is expected for the completion of the planed 2018 activity.

2.2.4 Stony Brook University

In general, there are no critical issues beside the preparedness of the clean-room facility.

2.2.5 University of Virginia

No critical issue other than the one related the high production cost of the GEM support frames for the large EIC-FT GEM prototype. We are working around for a cheaper option for procuring the frames.

2.2.6 Yale University

Nothing to report.

2.3 Additional information

2.3.1 Brookhaven National Lab

None

2.3.2 Florida Tech

None.

2.3.3 INFN Trieste

Further information is provided concerning the novel activity starting in 2018, which concerns a new photocathode based on NanoDiamond (ND) particles: the planned activity consists in initial studies to understand the compatibility of this innovative photocathode material with the operation in gaseous detectors. The possibility to use innovative photoconverters in gaseous detectors is a strategic option. In fact, so far, the only photoconverter compatible with large-size, operative gaseous detector is CsI. In spite of remarkable successful applications (for instance the read-out sensors of the ALICE RICH, the COMPASS RICH and the PHENIX HBD), the use of CsI in gaseous detector suffers of some intrinsic limitations: ageing, causing a severe decrease of the quantum efficiency after a collected charge of the order of some mC/cm^2 and long recovery time (about 1 d) after an occasional discharge in the detector. These limitations are related to the photon feedback from the multiplication region and to the bombardment of the CsI photocathode film by positive ions generated in the multiplication process. They impose to operate the detector at low gain, reducing the efficiency of single photoelectron detection. Alternatively, great care is required to reduce the IBF. Moreover, CsI is chemically fragile: if exposed, even for short time, to atmospheres with water vapour the molecule is broken and therefore the QE is lost. This feature imposes to assemble the photon detectors in clean, controlled atmospheres, making the overall detector construction tedious and complex. Therefore, the possibility of an alternative photocathode material adequate for gaseous detector is strategic.

The Quantum Efficiency (QE) of photocathodes by ND particles rich in graphite have been measured in vacuum: when the photocathode is hydrogenized, QE as high as 47% at 140 nm has been measured; globally, the quantum efficiency is non negligible in the VUV domain, below 210 nm. High QE-values have been measured both performing the hydrogen plasma treatment in situ (after forming the photocathode film on the substrate) and hydrogenizing the ND powder before coating the substrate with the photoconverting layer. The latter option is of great interest for gaseous photocathodes: if fact, the hydrogen plasma treatment requires high temperature ($> 800^O$C), not compatible with the components of gaseous detectors. When the ND powder is hydrogenized before the cathode coating, the spray procedure by an ultrasonic atomizer used to form the photocathode does not require temperatures exceeding 120^OC: this is compatible with gaseous detector components. Preliminary tests of mechanical attachment of the photocathode and ageing due to exposure to air indicate that this photocathode material is robust. A principle difficulty related to the photocathode material has to be considered in view of further studies: the ND powder provided by the producers is a cheap material not selected according to the graphite content, nor in grain-size; therefore several different samples have to be purchased and then the graphite-rich ones have to be selected by Raman spectroscopy; no exact reproducibility of the raw material from producers can be envisaged at present.

2.3.4 Stony Brook University

None.

2.3.5 University of Virginia

None.

2.3.6 Yale University

None.

3 Manpower

3.1 Brookhaven National Lab

This work is being carried out by members of the BNL Physics Department. It includes one Senior Scientist (C.Woody at 0.2 FTE), two Physics Associates (A.Kiselev and B.Azmoun at a combined effort of 1.2 FTEs) and one Senior Technician (W.Lenz at 0.3 FTE).

3.2 Florida Tech

- Marcus Hohlmann, Professor, 0.25 FTE, not funded under this R&D program.
- Matthew Bomberger, physics undergraduate student, not funded.
- Samantha Wohlstadter, physics undergraduate student, not funded.

3.3 INFN Trieste

From INFN Trieste:

- M. Baruzzo (Trieste University and INFN, undergraduated student)
- C. Chatterjee (Trieste University and INFN, PhD student)
- S. Dalla Torre (INFN, Staff)
- S. Dasgupta (INFN, postdoc)
- S. Levorato (INFN, Staff)
- F. Tessarotto (INFN, Staff)
- Y. Zhao (INFN, postdoc)

The contribution of technical personnel from INFN-Trieste is also foreseen according to needs.

From INFN BARI:

- Grazia Cicala (Bari University staff and INFN)
- Antonio Valentini (Bari University and INFN, professor)

Globally, the dedicated manpower is equivalent to 3 FTE.

3.4 Stony Brook University

- K. Dehmelt, Research Scientist, 0.3 FTE
- T. K. Hemmick, Professor, 0.1 FTE
- N. Ward, UG, 0.2 FTE

3.5 University of Virginia

None of the labor at UVa is funded by EIC R&D. The workforce is listed below:

- N. Liyanage; Professor; 0.1 FTE
- K. Gnanvo; Research Scientist; 0.4 FTE
- H. Nguyen; Research Scientist; 0.05 FTE
- J. Matter; Graduate Student; 0.1 FTE
- J. Siyu; Graduate Student; 0.1 FTE

3.6 Yale University

None of the labor at Yale is funded by EIC R&D. The workforce is listed below.

- R. Majka; Senior Research Scientist and Scholar; 0.1 FTE
- N. Smirnov; Research Scientist and Scholar; 0.5 FTE

-+

4 External Funding

4.1 Brookhaven National Lab

A BNL LDRD was obtained in early FY18 that will fund development of micropattern gas detectors for EIC and compliment our effort on MPGDs within the eRD6 Consortium. Actual funding will start in early calendar 2018 and is expected to last 3 years. The LDRD will support the two BNL Physics Associates at the level of 0.6 FTE along with MS&T of approximately $50K per year. The remaining BNL manpower is being paid by the BNL Physics Department.

4.2 Florida Tech

None.

4.3 INFN Trieste

INFN has assigned to this activity a support of 12 keuro for the year 2018.

Stony Brook University

There is no external funding for this R&D effort.

4.4 University of Virginia

UVa has DOE basic research grant from Medium Energy Physics. The R&D work on Cr-GEM is partly funded with the research grant.

4.5 Yale University

None.

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